Philippine Journal of Science
151 (1): 357-369, February 2022
ISSN 0031 - 7683
Date Received: 18 Aug 2021

Financial and Socio-economic Study of Modular Pyrolysis Facilities as Waste-to-Energy Technology: a Case Study in Metropolitan Manila, Philippines

Reynald Ferdinand Manegdeg[1,5,6], **Arturo Benedicto Ilano**[2], **Analiza Rollon**[3,5,6],
Eduardo Magdaluyo Jr.[4,5,6]*, and **Rinlee Butch Cervera**[4,5,6]

[1]Department of Mechanical Engineering, [2]Virata School of Business
[3]Department of Chemical Engineering
[4]Department of Mining, Metallurgical, and Materials Engineering
[5]Energy Engineering Program
[6]Environmental Engineering Program
College of Engineering, University of the Philippines Diliman
Quezon City 1101 Philippines

Industrial, medical, and electronic residual wastes can potentially be an important source of energy with the use of waste-to-energy (WtE) conversion technology. In Metropolitan Manila, Philippines, about 144,000 kg/d of residual wastes were being generated by the hospitals, industrial sectors, and electronic companies. Hence, imploring high potential benefits can be achieved through utilizing these wastes as feedstock for any WtE conversion facility. A technical and financial costing was performed to evaluate the feasibility of putting up a conventional pyrolysis system in Metropolitan Manila. Various modular-type scenarios of a pyrolysis system in the WtE facility were identified based on the geographical attributes of the sectoral residual wastes generators. Results showed that a 10 tons/d pyrolysis plant facility, with Brayton power set-up, can eventually produce 800 kW and generate an annual net income of PHP 83.63 M after a 2-yr breakeven period. In addition, this facility can accommodate at most 11 tons/d of residual wastes for processing. In contrast, a smaller footprint of pyrolysis-Brayton set-up consisting of three tons per day, with 1,000 kg of daily wastes and a power generation of 65 kW, can potentially produce a net income of PHP 18.06 M following a 3-yr breakeven period. The WtE business models of putting up conventional pyrolysis facilities, by presenting both the maximum and minimum scenarios in terms of plant capacity and income when intended for operation and adoption, were computed to be feasible.

Keywords: financial feasibility, pyrolysis technology, socio-economic study, waste-to-energy

INTRODUCTION

The lack of solid waste disposal facilities remains to be one of the biggest environmental issues in the country. This needs to be addressed by both the local government units (LGUs) and the industrial sectors. Consequently, littered and illegally dumped solid wastes have become increasingly visible in the streets, both private and public lands, rivers, lakes, beaches, coastal areas, and even offshore. Citizens and waste haulers frequently resort to open burning or open dumping, which have become difficult to control. Gaseous emissions from such illegal burning pollute the air. Leachate from open waste dumps contaminates soil and water. Such practices consequently

---

*Corresponding Author: edmagdauyo1@up.edu.ph threaten wildlife and human health. According to studies, the Philippines is among the top countries that contribute to marine debris (Jambeck *et al.* 2015). These wastes come mainly from land-based activities. Due to the increasing population, an evident decline in spaces and budget dedicated to sanitary landfills has pushed solid wastes disposal onto the country's surrounding bodies of water (Mayuga 2020).

Generation rates for both hazardous and non-hazardous wastes are skyrocketing. The Philippines' annual waste generation is projected to surge this year from 21,016,523 tons to 21,844,080 tons (Lagare 2021). Within Metropolitan Manila alone, the waste generation in 2021 is estimated to be more than 100,000 tons higher than that in 2020, *i.e.* 3,527,484 tons in contrast to the 3,406,662 tons in 2020 (Lagare 2021). Given the limited availability of needed treatment and disposal facilities, wastes are often sent to highly unsafe open dumps. About 90% of wastes in emerging economies like the Philippines are often disposed of in non-regulated dumpsites, openly dumped, or openly burned (WB 2019). Furthermore, relying on landfills that are poorly designed, poorly situated, or both also opens the risk of being exposed to fugitive emissions, leaks, and other potential health risks that may also affect neighboring communities (Masigan 2019; Lisk 1991; Vaverková 2019).

In an earlier study on the characterization of the medical, industrial, and electronic wastes covering the areas of Metropolitan Manila, it was determined that about 52,500 tons/y of residual wastes are generated with a total energy potential of about 4,440 GJ/d (Manegdeg *et al.* 2021a). This implies that there is a large amount of readily available feedstock to WtE systems, which can at least provide support to daily energy needs, as well as mitigate problems associated with the typical disposal of these hazardous and residual wastes. An estimate for the household total annual electricity consumption *per capita* in the National Capital Region (NCR) was 2,019.23 kWh *per capita* (Tayag and Lopez 2021), and this translates to a 1.9% supply from the potential energy generation of residual wastes. Hence, there is a need to build facilities that do not merely store wastes but can simultaneously reduce wastes volume through utilizing material and energy resources.

Currently, WtE technology solutions have been adopted successfully in developed countries and continue to emerge in developing countries as well, in parallel with the continuing improvement of sanitation systems worldwide. Among the environmental benefits of WtE are reducing the need for sanitary landfill space and eliminating the widespread open dumping of wastes. The latter activity has been among significant sources of greenhouse gases and hazardous air pollutants. Thus, WtE can improve the sanitation and health conditions of poor communities usually dwelling in near open waste dumps.

Pyrolysis, which is a type of WtE technology, involves thermal decomposition of lignocellulosic derivatives and other organic materials under an inert condition in an oxygen-deficient environment to produce energy-rich oil and synthetic gas. It is a method that is already recognized by the Philippine law, under the Toxic Substances and Hazardous and Nuclear Wastes Control Act of 1990 or Republic Act 6969, as one of the WtE technologies for treating hazardous wastes. In developed countries, the biogenic fraction of solid waste used as feedstock to WtE facilities is considered a renewable energy resource. In the Philippines, the Renewable Energy Act of 2008 or Republic Act 9513 deems WtE systems as among the means of harnessing the renewable energy content of wastes. Although the Philippine government is yet to build WtE facilities, there are ongoing efforts to legislate and establish a framework for WtE facilities in waste treatment and disposal, and to generate a sustainable source of energy. The government is promoting the use of state-of-the-art, environmentally sound, and safe non-burn technologies for the handling, treatment, thermal destruction, and disposal of sorted, unrecycled, and uncomposted municipal, bio-medical, and hazardous wastes. This is also the reason why the process of incineration or direct burning of municipal, bio-medical and hazardous wastes in the Philippines is banned based on the Philippine Clean Air Act of 1999 or Republic Act 8749. With the adoption of the WtE facility in the Philippines, there is the highest possible standards and guidelines being followed to ensure that all emissions and effluents in this process will comply with relevant environmental standards (DENR 2019).

Despite the availability of several WtE technologies worldwide, its applicability in the Philippine setting is yet to be established. However, given that pyrolysis technology is legally supported, this shows a highlight in finally integrating WtE technology into the Philippines. There are also limited studies in the economic analysis of WtE investment in the country. Most of the research studies related to industrial, medical, and electronic residual wastes include wastes analyses and characterization (Manegdeg *et al.* 2011; Montero *et al.* 2019; Payot and Pobar 2017; Lunag *et al.* 2019; Lunag and Elauria 2021), waste treatment and potential electricity generation (Manegdeg *et al.* 2020, 2021b), and electronic wastes estimation and recycling processes (Peralta and Fontanos 2006; Alam 2016; Yoshida *et al.* 2016). One economic study showed that WtE technologies in the Philippines are better options than continuing dumping wastes in landfills (Agaton *et al.* 2020). This research proposed an investment model to analyze the economic feasibility of WtE projects and highlighted incineration to be the most profitable option, followed by gasification and pyrolysis. Research in other countries related to financial feasibility model for WtE plants focused on technologies such as landfill gas to energy, incineration, and anaerobic digestion (Hadidi and Omer 2016, Ogunjuyogbe *et al.* 2017; Alzarte-Arias *et al.* 2018).

To further establish the potential of WtE technologies in Metropolitan Manila, there should be comprehensive research needed on how to finance and conclusively make it economically viable. Business models and enabling policies should be clearly outlined. In this paper, the researchers aim to contribute to how the industrial, medical, and electronic residual wastes in Metropolitan Manila can be utilized as a feedstock for WtE technology compared to the continuing use of the sanitary landfill. Thus, this study investigates the socio-economic impact of putting up a WtE facility using pyrolysis technology with an economic analysis model to determine the financial feasibility of the different WtE scenarios. Specifically, the financial viability of different business model scenarios was done based on the metrics such as breakeven analysis, calculation of return on investment (ROI), and determination of net present value (NPV).

METHODOLOGY

Waste profiling of industrial, medical, and electronic residual wastes in Metropolitan Manila was conducted among various medical facilities, electronic TSD (transport, storage, and disposal) facilities, and junk shops (Manegdeg *et al.* 2021a). Secondary data on hazardous wastes were then collected and derived from the self-monitoring report submitted by different industries. After which, a literature review on pyrolysis technology was synthesized to derive the appropriate WtE technology that would be most applicable and practical within the Philippine setting. Subsequently, an economic analysis on various types of modular pyrolysis setup was conducted. Three main pyrolysis plant options were identified – which include a 1-, 3-, and 10-ton plant capacity. The 1-ton plant, together with some 3-ton cases, was designed for on-site operations that have the capacity dedicated to large waste-producing locations, such as factories or hospitals. In contrast, the 10-ton plant was a proposed stand-alone centralized manufactory that collects and aggregates waste from nearby locations to process on its own dedicated site. For the power generation plant, there were five options – each corresponding to a different power output of 65, 200, 400, 800, and 1000 kW depending on the demand requirement.

To determine the feasibility of the WtE project, each individual plant was assessed for its profitability in a stand-alone capacity, as well as several key combinations of pyrolysis and power generation plants. It is assumed that each pyrolysis plant can operate for 330 d/yr, 24 h/d with a 5-yr lifespan, while the power generator plants can operate for 330 d/yr, 24 h/d with a 30-yr lifespan. The assumptions and parameters used for economic analysis are shown in Table 1 (Ji *et al.* 2017). The time value of money over the plant lifetime of 30 yr was also taken into consideration. The financial viability of the proposed scenarios was determined primarily through 1) breakeven analysis, 2) calculation of the ROI, and 3) determination of NPV. These metrics were selected due to their general acceptability and communications efficiency, particularly for transacting with investment participants.

Table 1. Criteria, key assumptions, and prices for economic analysis.

Parameter	Unit	Value	Remarks
Total lifespan	Years (yr)	30	
Bank loan interest Rate *per annum*	%	7	Payable for 10 yr
Gross income tax rate	%	5	After the 4-yr income tax holiday (ITH) and registered under the BOI (Board of Investment)
Other operating costs	%	2 (of initial capital cost)	The maintenance and repairs cost *per annum*, as well as the additional tax and other fees p*er annum*, is calculated as 2% of the initial capital cost
Additional tax and fees	%	2 (of initial capital cost)	
Waste disposal fee	PHP/kg	20,30,40; 28 (recommended)	Variable; indicated lowest possible price
Carbon credits	PHP/ton	504.49	Paper referenced pricing of carbon credits last 2011
Electricity sales	PHP/kWh	8.49	As of 2020 information
Tipping fee	PHP/ton	600	From Metropolitan Manila Development Authority (MMDA)
Corporate income tax (CIT)	%	30	Applied after 6th year of operation due to ITH incentive
Government share (GS)	%	1	Obtained from the gross income at the start of operation
Value-added tax on imported goods	%	12	Applied on purchases after 10th year of operation due to duty fee importation incentive

Because of the utility nature of the project, with cash flows expected to be relatively stable and predictable throughout the project life, it was expected that the above computations would yield consistent findings and conclusions. The corresponding equations for the calculations in the financial analysis are shown in Table 2 (Ayodele *et al.* 2018). The socio-economic assessment was discussed based on the business model scenarios of WtE conversion being presented using pyrolysis-Brayton power technology.

As this study is limited only to the residual wastes under investigation, other secondary data for industrial residual wastes were utilized, including information on the electronic wastes only from registered junkshops. For waste energy generation, pyrolysis was being considered and for Brayton power generation for energy conversion was utilized.

RESULTS AND DISCUSSION

The generated daily wastes from industrial, medical, and electronic residuals are about 143 tons/d, which has an energy potential of about 4,727 GJ/d. This was derived from the sum of the product of the total waste is derived per waste stream source and the average calorific value of the waste material (Manegdeg *et al.* 2021a). Given this energy potential, an estimation of its electricity generation using conventional pyrolysis is about 45 MW/d. With this electricity generation potential, a modular WtE is highly capable of supporting some of the electricity needs within Metropolitan Manila.

Conventional Pyrolysis Technology and Its Benefits

Conventional pyrolysis is just one among several types of WtE conversion technologies. Although the conventional pyrolysis method is reported to be not as widely established nor highly adopted yet in both

Table 2. Equations for financial analysis.

Parameter	**Equations**	**Remarks**
Fixed yearly operating cost	$\sum C_{cost\ factors}$	Labor Technical & management Fuel cost Transportation Electricity consumption Water consumption Maintenance & repairs Additional tax & other fees Fixed maintenance costs Variable maintenance costs Average maintenance costs
Total costs (TC)	$CC + OC + PR + PRF$	Parts replacement (PR) Permit renewal fees (PRF) Capital costs (CC) Operating costs (OC)
Total revenue (TR)	$CCr + WDF + ES$	Carbon credits (CCr) Waste disposal fee (WDF) Electricity sales (ES)
Net income without tax (C_{wot})	$TR - TC$	
Net income after tax (C_t)	$C_{wot} - GS - CIT$	Corporate income tax (CIT) Government share (GS) C_{wot} = net income without tax
Total profit after the lifespan	$\sum_{t=1}^{T} C_t$	C_t = net cash inflow during the period t
Return on investment (ROI)	$ROI = \frac{Return - Cost - Investment}{Investment}$	
Annualized ROI	$ROI_{multiple\ periods} = (1+r)^t - 1$	$ROI_{multiple\ periods}$ = cumulative return over all periods R = return per period (%) T = number of periods
Breakeven period	$C_{t+1} - C_t > 0$	Supposed the value returns positive, t + 1 is the breakeven period for the proposed setup

developed and developing countries (UNEP 2019), it has proven otherwise that it is more advantageous in diffusing significantly lower emissions in comparison to the usual combustion process, thus carrying a greater benefit towards long-term sustainability. As waste generation continues to speed up, the pyrolysis WtE facility can also provide safe and low-emissions solutions concerning the Philippines' waste management issues.

Among the WtE technologies, pyrolysis is also considered a zero-waste recovery process. Its product yields bio-oil, char, and non-condensable gases, which can be used downstream. The bio-oil can be utilized for heat or power generation and further processed as liquid fuels or feed for chemical production and synthesis. Conversely, the fuel gas is used to store and transfer heat to feed water or used directly in an internal combustion engine or in a gas turbine. This fuel gas usage facilitates the generation of heat or electricity through power generators. Prior to usage, the fuel gas may be cleaned to eliminate components that cause atmospheric pollution. Meanwhile, the char produced from the process may also be employed in construction or agricultural applications (Oladejo *et al.* 2018). Moreover, the subsequent diversion of waste from landfills and low emission production of electricity further shows the highly significant environmental benefits of the pyrolysis system. Every ton of residual wastes processed by the pyrolysis system can be considered one ton of waste diverted from landfills, and each kilowatt (kW) of electricity produced can be considered 1 kW of energy not derived from the burning of fossil fuels. This means that in a year, a single pyrolysis system keeps at least 330 tons of waste away from landfills and produces at least 21,450 kW of non-fossil fuel energy. Like other fossil-fuel-fed power plants, air pollutants may also be emitted from WtEs due to mismanagement. The emissions may include SO_x, hydrocarbons, carbon monoxide, particulate matter, greenhouse gases such as CO_2, dioxins, and furans are also emitted by different WtE technologies. However, these environmental emissions are highly dependent on the pollution control system of various plants. Hence, it is important that the proposed pyrolysis plants are both properly secured and controlled.

Pyrolysis, in itself, is also a very effective method for the treatment of various types of plastic waste materials. The adoption of a pyrolysis WtE system can be part of a solution to the plastic problem the country has faced for years (Vijayakumar and Sebastian 2018). Of the 2.7 M tons/y of plastic waste produced in the Philippines, only 70% is properly collected and disposed of. That leaves 890,000 tons of plastic unaccounted for; these often end up in open dumps, leaked into streams, rivers, lakes, and oceans, and generally littered (McKinsey & Co. 2015). The WtE facilities are a significant step forward in waste management that can effectively deal with the gargantuan amounts of plastic produced daily. For example, a study of the pyrolysis processing of scrap tires showed that the accumulation of wastes such as discarded tires poses serious environmental risks. Minimizing the volume of this non-biodegradable waste reduces the environmental and health risks of fire or ignition, as burning tires releases highly toxic waste in both soil and air. Carbon emissions are also significantly reduced in the pyrolysis of tires *vs.* other waste disposal methods (Neto *et al.* 2019).

Within the Philippines, it has been observed that certain problems caused by the increasing rates of hazardous medical waste have also put forward certain risks. According to data from the Philippines' Department of Environment and Natural Resources (DENR), there were 1303 registered hazardous waste generators in NCR in 2020, with only 14 registered TSD facilities (DENR 2020; DENR-EMB 2020). This leaves a considerable lack of capacity, with the potential for waste to be left untreated. The current disposal practices for medical waste include landfilling, chemical disinfection, and microwave and steam sterilization technologies. These methods release toxic substances such as pathogens, radioactive substances, and volatile compounds such as mercury that may penetrate the soil or underground water through landfills (PATH 2005; Hong *et al.* 2017). Currently, the Asian Development Bank estimates an additional 280 tons/d of hazardous waste due to the COVID-19 pandemic (ADB 2020). Given the pressing problem, a study conducted by Hong *et al.* (2017) discusses the environmental and economic impacts of the pyrolysis method as an alternative solution for medical waste disposal. The findings of the study show minimal mercury emissions for medical waste pyrolysis but higher direct hydrogen chloride emission compared to municipal solid waste and industrial hazardous waste incineration (Hong *et al.* 2017). Hence, with hazardous waste levels rising, pyrolysis can potentially be a key part of mitigating the consequences. Moreover, the economic impact is mostly related to the cost of investment, labor, electricity, and human health protection (Hong *et al.* 2017).

In addition to the previously mentioned risks, having to rely only on uncontrolled landfills as waste disposal areas can further amplify the risks, which the waste itself already carries. Steady carbon dioxide and methane emissions, as well as the risk of leakages into groundwater, make the nearby communities more vulnerable to health risks. Nonetheless, open dumping – despite having been declared illegal – still continues to proliferate. There are 331 illegal dumps that continue to operate despite closures made by the DENR (Lagare 2021). These unregulated waste dump sites are often mismanaged and are significant public health and sanitation risks to neighboring communities and the environment as well. Shifting towards pyrolysis systems will greatly help in mitigating the health risks of both landfills and open dumping. Pyrolysis WtE technology in an inert environment has only fuel gas and ash as the main outputs. Thus, if properly managed, it does not generate toxic or greenhouse gases, which can subsequently prevent any health risks such as respiratory diseases to its nearby communities. Furthermore, there is no evidence that proves the possible health risks that may occur due to the pyrolysis process (Neto *et al.* 2019; Oladejo *et al.* 2018).

Financial Analyses of Pyrolysis Modular Plants and Power Generation Plant

Except for direct combustion WtE systems, WtE projects typically have two-component plants: the pyrolysis plant and the power generation plant. The pyrolysis plant processes the feedstock waste materials into fuel oil, synthetic gas, and char – where synthetic gas byproducts are then used by the power generation plant to generate electricity.

The initial capital expenditure for each of the modular pyrolysis and power generation plants is presented in Table 3. Three pyrolysis plants with capacities of 1, 3, and 10 tons/d (Manegdeg *et al.* 2021b) plus five Brayton power generators with net operating capacities of 65, 200, 400, 800, and 1000 kW are considered (US EPA 2015). The initial capital investment for putting up a pyrolysis plant includes the costs incurred for the procurement of the pyrolysis system, land cost, building and construction, and loaders. The average unit price of the land in Metropolitan Manila is assumed to be PHP 30,000/m^2 and the average cost of industrial construction is assumed to be PHP 8,734/m^2, as reported by the Philippine Statistics Authority in 2020. Operating as a stand-alone facility, a 10-ton pyrolysis plant will require loaders for transportation. One tipper truck and one loader truck were added as an additional expense to be used for the transportation of feedstock to the plant site.

Increasing waste feedstock capacity and power generation increases the total capital cost (Table 3). A 10-ton pyrolysis plant has a capital expenditure of PHP 14.64 M, which has a 117% increase from that of a 3-ton pyrolysis plant. Moreover, from 65- to 1000-kW power generation, the capital cost is increased by PHP 193.19 M or an equivalent change of 300%.

The expenses, revenues, and annual income expected for each modular plant are shown in Table 4. The total operating costs for the pyrolysis plant consist of the costs for labor, electric and water consumption, maintenance and repairs, taxes, and other fees. The annual labor cost is calculated based on the current average salary for the corresponding position for energy-related facilities (BOI-ISD 2018). The current electricity rate is at PHP 8.4911/kWh as provided by Meralco, while the current water consumption rate is at PHP 28.52/cm^3 as provided by Manila Water (CNN Philippines 2020). The electric consumption of the plant is estimated based on the power output of the pyrolysis plants, which is 3 kW for each pyrolyzer, and the plant is assumed to consume 10 m^3 of water per ton of waste. The maintenance and repair cost *per annum*, as well as the additional tax and other fees *per annum*, is calculated as 2% of the initial capital cost (Ji *et al.* 2017). As seen in Table 4, the equivalent annual net income of a 10-ton pyrolysis plant is PHP 68.44 M, which is 453% higher compared to that of the 3-ton pyrolysis plant at PHP 15.10 M. Moreover, a higher annual net income was computed for a 1000-kW power generation, valued at PHP 16.48 M compared to a 400-kW power generation at PHP 6.76 M.

The cost for parts replacement every 5 yr for pyrolysis plants is also taken into consideration in the calculation (Table 4). On the other hand, the revenue that will be generated by the WtE project will come from waste disposal fees, tipping fees, carbon credits, and electricity generation. A waste disposal fee is charged for the amount of hazardous waste disposed of by the customers at their respective landfill areas. The current market pricing of waste disposal fees is PHP 40.00/kg. The waste disposal

Table 3. Capital expenditure for modular plants using pyrolysis-Brayton (PHP M).

Capital expenditure	1-ton	3-ton	10-ton	65 kW	200 kW	400 kW	800 kW	1000 kW
Pyrolysis system	0.73	1.70	2.67	–	–	–	–	–
Power generator	–	–	–	6.21	19.31	34.01	65.72	78.19
Land	3.00	3.90	5.40	0.03	0.18	0.36	0.72	0.90
Building & construction	0.87	1.14	1.57	–	–	–	–	–
Loaders	–	–	4.99	–	–	–	–	–
Installation fees	–	–	–	9.44	28.75	49.58	96.08	114.10
Total capital cost	4.60	6.74	14.64	15.68	48.24	83.95	162.52	193.19

Table 4. Operational expenses and revenues for modular plants (PHP M).

Parameters	1-ton	3-ton	10-ton	65 kW	200 kW	400 kW	800 kW	1000 kW
Total operational expenses	7.91	9.26	14.65	1.07	3.55	5.90	11.24	16.04
Employment	5.73	6.02	7.53	–	–	–	–	–
Electricity	0.23	0.23	0.23	–	–	–	–	–
Transportation	0.00	0.00	0.01	–	–	–	–	–
Water	0.11	0.31	1.03	–	–	–	–	–
Maintenance & repairs (annual, fixed)	0.92	1.35	2.93	0.52	1.59	3.19	4.78	7.97
Taxes and other fees	0.92	1.35	2.93	–	–	–	–	–
Maintenance and repairs (variable)	–	–	–	0.19	0.59	1.19	2.38	2.97
Maintenance and repairs (average)	–	–	–	0.36	1.36	1.53	4.08	5.10
Parts replacement (every 5 years, annualized)	0.16	0.38	0.60	–	–	–	–	–
Total revenue	7.65	22.95	78.49	2.20	6.84	13.33	27.81	34.22
Tipping fee	–	–	1.98	–	–	–	–	–
Waste disposal fee	8.38	25.15	83.82	–	–	–	–	–
Carbon credits	0.17	0.50	1.66	–	–	–	–	–
Electricity sales	–	–	–	2.20	6.84	13.33	27.81	34.22
Operating income (annual)	0.64	16.39	72.82	1.13	3.30	7.42	16.57	18.19
Income tax	0.43	1.28	4.37	0.11	0.34	0.67	1.39	1.71
Net income	0.21	15.10	68.44	1.02	2.96	6.76	15.18	16.48

fee for the pyrolysis plants, for this analysis, is assumed to be PHP 28.00 to match against the mentioned current market and is also found to be the lowest possible price that is profitable across the board for each of the pyrolysis plants. The net income of 1-, 3- and 10-ton pyrolysis plants at various waste disposal fees are presented in Table 5 for comparison.

Table 5. Waste disposal fees and net annual income per pyrolysis plant (PHP M).

Net income based on waste disposal fee	1-ton	3-ton	10-ton
PHP 20	–2.07	8.28	45.69
PHP 28	0.21	15.10	68.44
PHP 30	0.78	16.81	74.13
PHP 40	3.62	25.34	102.57

The tipping fee is the amount charged for a quantity of waste that will be processed in the facility. The current tipping fee provided by the Metropolitan Manila Development Authority (MMDA) is at PHP 600/ton of waste. However, it can be assumed that the MMDA will increase the waste disposal subsidy for WtE facilities since the current charge is for landfill costs only and, thus, the tipping fee can be estimated at PHP 3,700/ton (AECOM 2016). On the other hand, a carbon credit is a permit that allows any institution to emit a certain amount of carbon emissions according to the 1997 United Nations' Kyoto Protocol. A mass of 1 ton of carbon emission is allowed per one carbon credit. A certain carbon credit limit is set to an institution for the carbon emission it is allowed to produce. Unused carbon credits are incentivized through potentially saving and reselling their emission allowances. Moreover, carbon credits can also be issued from the carbon emissions avoided by the WtE facility, which are considered certified emission reductions (CERs). Current CER trading in the market is priced at around PHP 504.49/ton of carbon emission avoided (Kenton 2020; Philippine Daily Inquirer 2011). Considering all the mentioned sources of revenues, the profitability of each of the modular plants of various capacities is summarized in Table 6.

Business Model Scenarios

To further investigate the benefits of putting a pyrolysis system in Metropolitan Manila, various potential business models were identified based on the five pyrolysis-power generator combinations. Since the outputs of the pyrolysis process will serve as the inputs for the power generation process, the pyrolysis plants' capacity and output must also be parallel with the processing capacity

Table 6. Profitability of modular plants (PHP M).

Parameters	1-ton	3-ton	10-ton	65 kW	200 kW	400 kW	800 kW	1000 kW
Total capital cost	4.60	6.74	14.64	15.68	48.24	83.95	162.52	193.19
Total operational expenses	7.91	9.26	14.65	1.07	3.55	5.90	11.24	16.04
Total revenue	8.55	25.65	87.47	2.20	6.84	13.33	27.81	34.22
Annual operating income	0.64	16.39	72.82	1.13	3.30	7.42	16.57	18.19
Income tax	0.43	1.28	4.37	0.11	0.34	0.67	1.39	1.71
Net income	0.21	15.10	68.44	1.02	2.96	6.76	15.18	16.48
Breakeven period (yr)	23	1	1	16	17	13	11	12
Profit after lifespan	1.67	446.37	2,038.70	14.85	40.42	118.77	293.00	301.06
ROI afterlife (%)	36.36	6625.39	13928.90	94.74	83.79	141.48	180.29	155.84

Table 7. Proposed business models.

Business model scenario	Pyrolysis plant capacity (ton)	Brayton power generator (kW)	Purpose
A	1	65	To accommodate facilities that generate ≤ 1.1 ton/d of waste that can produce at least 65 kW of electricity
B	3	200	To accommodate facilities that generate ≤ 3.3 tons/d of waste that can produce at least 200 kW of electricity
C	3	400	To accommodate facilities that generate ≤ 3.3 tons/d of waste that can produce at least 400 kW of electricity
D	10	800	To accommodate facilities that generate ≤ 11 tons/d of waste that can produce at least 800 kW of electricity
E	10	1000	To accommodate facilities that generate ≤ 11 tons/d of waste that can produce at least 1,000 kW of electricity

of each power generator. These business models are simply recommendatory and are inclusive of setups that propose pyrolysis and power generation plants to be mixed and matched as needed. The business models and their potential purposes are presented in Table 7, while the potential income generated from the various models and their respective expenditures are shown in Table 8a to indicate their profitability.

The scenarios were also assessed as to their NPV. The NPV metric easily presents the present value of each plant option, given their respective streams of capital outlays and inflows of revenues. This provides a convenient manner by which to assess the viability of each option, enabling potential investors to immediately see the PHP value of each business model. The NPVs for each business model are presented in Table 8b, which shows different scenarios for each business model depending on the assumed or expected cost of money, *i.e.* lending rate or opportunity cost to investors. The table shows results that are consistent with that of Table 8b, in that the 10-ton/800kW offers the most optimal value for the investment, yielding from PHP 596 M–1.16 B in present value for the investment, depending on the cost of capital.

Socio-economic Impact

The establishment of pyrolysis systems can be of immense benefit in ensuring quicker and more efficient post-disaster cleanups. Metropolitan Manila and the rest of the Philippines are highly susceptible to intense rains, strong typhoons, and flash floods. These often cause immense damage and detrimental effects not only to the environment but also to human health, which cascades to all aspects such as social and economic impacts. Typhoons or just heavy rains cause floods due to wastes from dumpsites or those improperly disposed of that blocks waterways such as canals and rivers. This is in addition to bad health effects and livelihood risks caused by flooding. Given the frequency of storms and typhoons in the Philippines, proper waste disposal plays a key role in disaster resilience as pyrolysis systems

Table 8a. Profitability of proposed business models (PHP M).

Costing	1-ton/ 65 kW	3-ton/ 200 kW	3-ton/ 400 kW	10-ton/ 800 kW	10-ton/ 1000 kW
Capital cost	20.28	54.98	90.69	177.16	207.82
Pyrolysis system	0.73	1.70	1.70	2.67	2.67
Power generator	6.21	19.31	34.01	65.72	78.19
Land	3.03	4.08	4.26	6.12	6.30
Building & construction	0.87	1.14	1.14	1.57	1.57
Loaders	0.00	0.00	0.00	4.99	4.99
Installation fees	9.44	28.75	49.58	96.08	114.10
Yearly operation	8.98	12.81	15.17	25.89	30.69
Employment	5.73	6.02	6.02	7.53	7.53
Electricity	0.23	0.23	0.23	0.23	0.23
Transportation	0.00	0.00	0.00	0.01	0.01
Water	0.11	0.31	0.31	1.03	1.03
Maintenance (annual, fixed)	1.44	2.94	4.53	7.71	10.89
Taxes/other fees	0.92	1.35	1.35	2.93	2.93
Maintenance and repairs (variable)	0.19	0.59	1.19	2.38	2.97
Maintenance and repairs (average)	0.36	1.36	1.53	4.08	5.10
Parts replacement (every 5 yr)	0.16	0.38	0.38	0.60	0.60
Revenue per year	10.75	32.49	38.98	115.28	121.69
Tipping fee	0.00	0.00	0.00	1.98	1.98
Waste disposal	8.38	25.15	25.15	83.82	83.82
Carbon credits	0.17	0.50	0.50	1.66	1.66
Electricity sales	2.20	6.84	13.33	27.81	34.22
Yearly operating income	1.77	19.68	23.81	89.39	91.00
Income tax	0.54	1.62	1.95	5.76	6.08
Net income	1.23	18.06	21.86	83.63	84.92
Breakeven (yr)	17	3	4	2	3
Profit after lifespan	16.52	535.53	623.61	2504.62	2522.30
ROI (%)	81.49	974.10	687.65	1413.80	1213.67

Table 8b. NPV of business models (PHP M).

Business plan scenario	Lending rate			
	2%	4%	6%	8%
1-ton/ 65 kW	(0.16)	(3.43)	(5.82)	(7.60)
3-ton/ 200 kW	235.61	183.14	143.55	113.27
3-ton/ 400 kW	261.52	198.46	150.98	114.75
10-ton/ 800 kW	1,166.97	922.50	737.80	596.23
10-ton/ 1000 kW	1,157.59	909.88	722.84	579.57

can provide efficient and effective waste disposal and treatment, especially given the increasing lack of holding capacity in sanitary landfills. Moreover, a WtE facility also provides social benefits such as local employment. The establishment of the facility will provide job opportunities in construction and initial operations. Afterward, as part of regular operations, the facility will employ skilled workers as staff for environmental monitoring, facility design, administration and procurement, transport and delivery, and operations and maintenance (The State of Victoria Department of Environment, Land, Water and

Planning 2017).

The increasing number of materials recovery facilities and recycling initiatives may increase the amount of residual waste collection and, thus, can help sustain the WtE of residual wastes. Utilizing only residual and hazardous wastes for WtE conversion may also improve the working conditions for the informal recyclers (UNEP 2019). Through direct and indirect job opportunities in the city surrounding the pyrolysis, the facility could lead to better access to food, housing, health care, and education. Consequently, increasing the generation of capital and commerce around the region will increase the trade in goods and services and tax collection, respectively. Thus, cities and municipalities may invest in the establishment and development of better public spaces, hospitals, and schools (Neto *et al.* 2019).

Even in the tourism sector, there are also implications of having a good solid waste management system. Tourism can provide a high level of income and employment plus, at the same time, environmental repercussions are at stake due to more generation of solid wastes (Mihai 2013; Chaabane *et al.* 2019). The diversion of wastes from landfills to WtE facilities can promote a clean environment and reduction of the volume of wastes can create a clean and good image of a particular destination. Poor management of waste, resulting in beach and street pollution, could damage the image of a place and cause economic suffering to local recreation and tourism industries. Thus, the satisfaction of tourists – either local or international – is greatly affected by the cleanliness and hygiene of a destination such as hotels, streets, and establishments (Chaabane *et al.* 2019).

Relevant stakeholders' consultation and approval – which include the government, environmental, and health authorities, community, and waste and energy sectors – are important in the implementation of a WtE technology project. Possible opposition from the community, local citizens, and non-governmental environmental organizations could occur due to health and environmental safety concerns. Thus, a feasibility study of the WtE technology, which includes cost-benefit analysis and environmental impact assessment accomplished by the cities and municipalities will raise public awareness of the planning progress (UNEP 2019).

With the current pandemic due to COVID-19, there is a steady increase in the number of face masks and other medical wastes. An estimate showed that the Philippines has a daily consumption of around 49 M pieces of face masks (Sangkham 2020). The overproduction of disposable gowns, gloves, respirators, face shields, and other plastics wastes from hospitals imposed additional challenges in solid waste management due to the pandemic (Klemes *et al.* 2020; Fadare and Okoffo 2020). It is very necessary that an appropriate separation, storage, and collection for recyclables and residual wastes must be adopted. Having an alternative technology, aside from a practice of dumping and open landfills, to reduce these medical wastes such as a WtE facility is very timely.

CONCLUSION AND RECOMMENDATION

This study evaluated the financial and socio-economic impacts of modular pyrolysis as a WtE facility with a case study in Metropolitan Manila. Considering the conventional pyrolysis technology for energy conversion and the Brayton cycle for power generation, this investigation was able to prove one viable business model scenario that covers a 10-ton/d pyrolysis plant facility, with a corresponding energy generation of 800 kW Brayton power set-up. Moreover, a smaller energy conversion capacity can also be feasible and established near the source of waste generators. This study also illustrates that the WtE project must be seen as part of a general shift towards safer, more efficient, and more sustainable waste management. There are clear social benefits of pursuing WtE systems, which go hand in hand with avoiding overfilling landfills and mitigating open dumping. The pyrolysis project has the potential to play a key role in mitigating risks such as increasing levels of hazardous waste, post-disaster waste management, and health risks due to waste leakages. As such, different site recommendations for a pyrolysis plant can be made due to the differing nature of the waste each type of establishment generates, as well as the amount of waste generated in each LGU. For medical wastes, some hospitals in these LGUs can convert their existing materials recovery facilities as holding areas for a nearby pyrolysis plant. For industrial and electronic wastes, the pyrolysis plant must be located in areas with a high density of manufacturing facilities to shorten the travel distance of the hauled wastes and to minimize the cost of transporting co-generated heat to these facilities. These arrangements ensure the sustainability of pyrolysis as an appropriate waste to energy technology to address Metropolitan Manila's waste problem.

Limited studies are available related to the financial and economic feasibility of modular WtE facility using pyrolysis technology with feeds coming from residual wastes. The results and analysis of this study can provide significant data that the findings can encourage other countries about the feasibility of modular waste WtE facilities using residual and even infectious waste as feedstocks.

For future research, this work can be extended to include sensitivity analyses on the economic viability of WtE technologies to investigate the influence of other variables such as electricity generation efficiency, capacity factor, *per capita* waste generation rate, population growth rate, and waste collection rate. A life cycle assessment study can be further conducted to assess the direct and indirect impacts of the proposed WtE business plan scenarios. Moreover, in order to come up with a comprehensive estimate for the integrated WtE systems, additional research can be included for the electricity transmission and distribution costs.

ACKNOWLEDGMENTS

This project is financially supported by the Philippine Senate Committee on Energy and the Energy Research Fund of the Office of the Vice-President for Academic Affairs, University of the Philippines Diliman. The authors also would like to acknowledge the research assistance of Jan Carlo Palomares, Christine Mae Macalisang, Jessa Hablado, Pearl Diamansil, and Evelyn Ulpindo.

REFERENCES

AECOM. 2016. Pre Feasibility Study – Conventional Waste-to-Energy Project. Retrieved from https://events.development.asia/system/files/materials/2016/12/201612-prefeasibility-study-conventional-waste-energy-project-quezon-city- philippines.pdf

AGATON CB, GUNO CS, VILLANUEVA RO, VILLANUEVA RO. 2020. Economic analysis of waste-to-energy investment in the Philippines: a real options approach. Appl Energy 275: 115265. doi: https://doi.org/10.1016/j.apenergy.2020.115265

ALAM Z. 2016. The assessment of the e-waste management generated from cellular phones, laptops, and personal computers in the Philippines. Manila Journal of Science 9: 27–42.

ALZARTE-ARIAS S, JARAMILLO-DUQUE A, VILLADA F, RESTREPO-CUESTAS B. 2018. Assessment of government incentives for energy from waste in Colombia. Sustainability 10(4): 1–16. doi: 10.3390/su10041294

[ADB] Asian Development Bank. 2020. Managing infectious medical waste during the COVID-19 pandemic. Retrieved from https://www.adb.org/sites/default/files/publication/578771/managing-medical-waste-covid19.pdf

AYODELE TR, OGUNJUYIGBE ASO, ALAO MA. 2018. Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria. Journal of Cleaner Production 203: 718–735. doi: https://doi.org/10.1016/j.jclepro.2018.08.282

[BOI-ISD] Board of Investments–Industry Studies Department. 2018. Renewable Energy – Human Resources. Retrieved from https://boi.gov.ph/wp-content/uploads/2018/02/Renewable-Energy.pdf

CHAABANE W, NASSOUR A, BARTNIK, S, BÜNEMANN A, NELLES M. 2019. Shifting towards sustainable tourism: organizational and financial scenarios for solid waste management in tourism destinations in Tunisia. Sustainability 11(13): 3591. doi: 10.330/su11133591

CNN PHILIPPINES. 2020. Meralco rates down anew August. Retrieved from https://cnnphilippines.com/news/2020/8/10/Meralco-rates-down-August- 2020.html

[DENR] Department of Environment and Natural Resources. 2019. Administrative Order No 2019-21: guidelines governing waste-to-energy facilities for the integrated management of municipal solid wastes. p. 1–7. Retrieved from https://denr.gov.ph/uploads/rmdd/dao-2019-21.pdf

[DENR] Department of Environment and Natural Resources. 2020. Registered hazardous waste generators (HWGs). Retrieved from https://app.powerbi.com/view?r=eyJrIjoiMTA2NzIzZDMtNTFjMC00NmUzLWIyOTYtODM5NTE2YTA1MzUwIiwidCI6ImY2ZjRhNjkyLTQzYjMtNDMzYi05MmIyLTY1YzRlNmNjZDkyMCIsImMiOjEwfQ%3D%3D&pageName=ReportSection&fbclid=IwAR294tJSt3NoQrSUICEBXW-JZ1f0r6uSUioVZYZ_NeOcgTS3i2L2QWKc4kQ

[DENR-EMB] Department of Environment and Natural Resources–Environmental Management Bureau. 2020. Registered Treatment, Storage, Disposal Facilities (TSDs). Retrieved from https://app.powerbi.com/view?r=eyJrIjoiMGQzNGQ2MDQtOTc3Yi00ZWU4LTkyZDMtZjljN2Y0ZTZmMzAxIiwidCI6ImY2ZjRhNjkyLTQzYjMtNDMzYi05MmIyLTY1YzRlNmNjZDkyMCIsImMiOjEwfQ%3D%3D&fbclid=IwAR0sKje64cU0v3GK4200UKZhHtDZZRI7pqS50W5K3L_i7Kfx4WzENAwQZsM

FADARE O, OKOFFO E. 2020. Covid-19 face masks: a potential source of microplastic fibers in the environment. Sci Total Environ 737: 1–4. doi: 10.1016/j.scitotenv.2020.140279

HADIDI L, OMER MM. 2016. A financial feasibility model of gasification and anerobic digestion waste-to-energy (WtE) plants in Saudi Arabia. Waste Management XXX: 1-12. doi: http://dx.doi.org/10.1016/j.wasman.2016.09.030

HONG J, ZHAN S, YU, Z, HONG J, QI C. 2017. Life-cycle environmental and economic assessment of medical waste treatment. J Cleaner Prod 174: 65–73. doi: 10.1016/j.jclepro.2017.10.206

KENTON W. 2020. Carbon Credit. Investopedia. Retrieved from https://www.investopedia.com/terms/c/carbon_credit.asp#:~:text=A%20carbon%20credit%20is %20a,one%20ton%20of%20carbon%20 dioxide

KLEMES JJ, FAN YV, TAN R, JIANG P. 2020. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. Renew Sust Energ Rev 127: 1–7. doi: https://doi.org/10.1016/j.rser.2020.109883

JAMBECK J, GEYER R, WILCOX C, SIEGLER T, PERRYMAN M, ANDRADY A, NARAYAN R, LAW KL. 2015. Plastic waste inputs from land into the ocean. Science 347(6223): 768-771. doi: 10.1126/science.1260352

JI LQ, ZHANG C, FANG JQ. 2017. Economic analysis of converting a waste agriculture biomass into liquid fuel: a case study on a biofuel plant in China. Renew. Sustain Energy Rev 70: 224-229. doi: https://doi.org/10.1016/j.rser.2016.11.189

LAGARE JB. 2021. Only 25% of LGUs have landfills. Retrieved from https://www.manilatimes.net/2020/02/12/news/regions/only-25-of-lgus-have-landfills/684028/

LISK DJ. 1991. Environmental effects of landfills. Sci. Total Environ. 100: 415–468. doi: https://doi.org/10.1016/0048-9697(91)90387-T

LUNAG M, ELAURIA J. 2021. Characterization and management status of household biodegradable waste in an upland city of Benguet, Philippines. Journal of Material Cycles and Waste Management 23: 840–853. doi: https://doi.org/10.1007/s10163-020-01167-3

LUNAG M, DURAN J, BUYUCAN E. 2019. Waste analysis and characterization study of a hill station: a case study of Baguio City, Philippines. Waste Management & Research 37(11): 1102–1116. doi: https://doi.org/10.1177/0734242X19866249 2019

MANEGDEG F, ROLLON A, MAGDALUYO, JR E, BALLESTEROS F, DE SALES-PAPA L, CLEMENTE E, MACAPINLAC E, IBANEZ R, CERVERA RB. 2021a. Waste profile and waste-to-energy conversion potential of medical, hazardous, industrial, and electronic residual wastes in Metro Manila, Philippines. Philipp J Sci 150(4): 611–623.

MANEGDEG RF, ROLLON A, BALLESTEROS, JR F, MAGDALUYO, JR E, DE SALES-PAPA L, CLEMENTE E, MACAPINLAC E, IBANEZ R, CERVERA RB. 2021b. Multi-attribute assessment of waste-to-energy technologies for medical, industrial, and electronic residual wastes. J. Energy Resour. Technol. p. 1–44. doi: https://doi.org/10.1115/1.4053024

MANEGDEG F, CORONADO L, PANA R. 2020. Medical waste treatment and electricity generation using pyrolyzer-rankine cycle for specialty hospitals in Quezon City, Philippines. IOP Conf Series: Earth and Environmental Science 463: 1–7.

MANEGDEG F, PAPA L, PAMINTUAN G, RANESES N, ALCAYDE A, BALLESTEROS F. 2011. Quezon City solid waste controlled disposal facility: waste analysis and characterization study. Philippine Engineering Journal 32(2): 31–50.

MASIGAN A. 2019. A solution to Metro Manila's garbage problem. Retrieved from https://www.bworldonline.com/a-solution-to-metro-manilas-garbage-problem/?fbclid=IwAR3cU8eMJDcUhqWx2O2lrjFpTY1-qGw2q6__OObfWgw3fhXGXEsOg0NJbao

MAYUGA JL. 2020. PHL only has 10 percent of needed sanitary landfills, says DENR exec. Retrieved from https://businessmirror.com.ph/2020/02/05/phl-only-has-10-percent-of-needed-sanitary-landfills-says-denr-exec/#:~:text=Twenty%20years%20after%20the%20enactment,for%20the%20proper%20disposal%20of

McKINSEY AND COMPANY. 2015. Stemming the Tide: Land-based strategies for a plastic-free ocean. Retrieved from https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/saving%20the%20ocean%20from%20plastic%20waste/stemming%20the%20tide%20full%20report.pdf

MIHAI FC. 2013. Tourism implications on local waste management. Case study: Neamț County, Romania. Present Environment and Sustainable Development, de Gruyter Open 7(1): 214–221. doi: 10.5281/zenodo.19119

MONTERO S, HAPINAT H, PENAFLORIDA M. 2019. Waste analysis and characterization study (WACS): measures towards effective municipal waste management in Batad, Iloilo, Philippines. Food and Fertilizer Technology Center for the Asian and Pacific e-Journal. Retrieved from https://ap.fftc.org.tw/article/1650

NETO GCD, CHAVES LEC, PINTO LFR, SANTANA JCC, AMORIM MPC, RODRIGUES MJF. 2019.

Economic, environmental and social benefits of adoption of pyrolysis process of tires: a feasible and ecofriendly mode to reduce the impacts of scrap tires in Brazil. Sustainability 11(7): 1–18. doi: https://doi.org/10.3390/su11072076

OGUNJUYOGBE ASO, AYODELE TR, ALAO MA. 2017. Electricity generation from municipal solid waste in some selected cities of Nigeria: an assessment of feasibility, potential and technologies. Renewable and Sustainable Energy Reviews 80: 149–162. doi: https://doi.org/10.1016/j.rser.2017.05.177

OLADEJO J, SHI K, LUO X, YANG G, WU T. 2018. A review of sludge-to-energy recovery methods. Energies 12(1): 60. doi: https://doi.org/10.3390/en12010060

[PATH] Program for Appropriate Technology in Health. 2005. Treatment alternatives for medical waste disposal. Program for appropriate technology in health, USA. Retrieved from https://path.azureedge.net/media/documents/TS_trt_alt_med_wst_disp.pdf

PAYOT C, POBAR R. 2017. Waste characterization, quantification and residents' perception towards solid waste management in Ubay, Bohol. International Journal of Environmental and Rural Development 8(2): 25–30. doi: https://doi.org/10.32115/ijerd.8.2_25

PERALTA G, FONTANOS P. 2006. E-waste issues and measures in the Philippines, J. Material Cycles and Waste Management 8: 34–39. doi: https://doi.org/10.1007/s10163-005-0142-5

PHILIPPINE DAILY INQUIRER. 2011. Trading carbon credits. Retrieved from https://business.inquirer.net/12897/trading-carbon-credits

SANGKHAM S. 2020. Face mask and medical waste disposal during the novel COVID-19 pandemic in Asia, Case Studies in Chemical and Environmental Engineering 2: 100052. doi: https://doi.org/10.1016/j.cscee.2020.100052

TAYAG CR, LOPEZ NS. 2021. Energy equity analysis in Metro Manila using household expenditure data. IOP Conf Ser: Mater Sci Eng 1109: 012043.

THE STATE OF VICTORIA DEPARTMENT OF ENVIRONMENT, LAND, WATER, AND PLANNING. 2017. Turning waste into energy. Retrieved from https://engage.vic.gov.au/

[WB] The World Bank. 2019. Solid waste management. Retrieved from https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management.

[UNEP] United Nations Environment Programme. 2019. Waste to energy: considerations for informed decision-making. Technology for Environment. p. 1–58.

[US EPA] United States Environmental Protection Agency. 2015. Catalog of Combined Heat and Power (CHP) Technologies. p. 55–56. Retrieved from https://www.epa.gov/sites/default/files/2015- 07/documents/catalog_of_chp_technologies.pdf

VAVERKOVÁ MD. 2019. Landfill impacts on the environment – review. Geosciences 9(10): 431. doi: https://doi.org/10.3390/geosciences9100431

VIJAYAKUMAR A, SEBASTIAN J. 2018. Pyrolysis process to produce fuel from different types of plastic – a review. IOP Conf Ser: Mater Sci Eng 396: 012062. doi: 10.1088/1757-899X/396/1/012062

YOSHIDA A, TERAZONO A, BALLESTEROS F, NGUYEN DQ, SUKANDAR S, KOJIMA M, SAKATA S. 2016. E-waste recycling processes in Indonesia, the Philippines, and Vietnam: A case study of cathode ray tube TVs and monitors. Resources, Conservation and Recycling 106: 48–58. doi: https://doi.org/10.1016/j.resconrec.2015.10.020