Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-15

DOI: *10.15244/pjoes/216345*

ONLINE PUBLICATION DATE: 2026-05-25

Original Research

Techno-Enviro-Economic Assessment of Hydrodrive-Incinerator Waste-to-Energy Technology in Bogor City

Heri Apriyanto[1], Mien Askinatin[2], Noorish Heldini[3], Taufiq Dwi Tamtomo[1], Nugraheni Setiastuti[1]*, Agusta Samodra Putra[1], Suhandojo Suhandojo[4], Binuko Dani Soewargono[5], Oni Hidayati[6], Anisa Fadhillah Widyani[6], Citra Ardiana[7], Yanuar Iman Dwiananto[1], Heru Mulyono[8], Sherafina Reni Cahayanti[1], Dhita Ayu Pradnyapasa[4]

[1]Research Center for Sustainable Industrial and Manufacturing Systems, National Research and Innovation Agency (BRIN), the B.J. Habibie Science and Technology Area (KST), South Tangerang 15314, Indonesia
[2]Directorate for Policy Evaluation of Research, Technology, and Innovation, National Research and Innovation Agency (BRIN), B.J. Habibie Building, Central Jakarta 10340, Indonesia
[3]Directorate for Economy, Employment, and Regional Development Policy, National Research and Innovation Agency (BRIN), B.J. Habibie Building, Central Jakarta 10340, Indonesia
[4]Research Center for Domestic Government, National Research and Innovation Agency (BRIN), Sarwono Prawirohardjo Science Area, South Jakarta 12710, Indonesia
[5]Directorate for Measurement and Indicators of Research, Technology, and Innovation, National Research and Innovation Agency (BRIN), B.J. Habibie Building, Central Jakarta 10340, Indonesia
[6]Bogor City Government, Bogor City 16122, West Java, Indonesia
[7]Directorate of Scientific Collection Management, National Research and Innovation Agency (BRIN), the Soekarno Science and Technology Area (KST), Bogor Regency, West Java 16915, Indonesia
[8]Research Center for Behavioral and Circular Economics, National Research and Innovation Agency (BRIN), Sarwono Prawirohardjo Science Area, South Jakarta 12710, Indonesia

Received: 08 August 2025
Accepted:02 January 2026

Abstract

Waste-to-Energy (WtE) technology offers a reliable, sustainable waste management approach. Integrating circular economy principles enhances sustainability and cuts costs. Despite Indonesia's environmental and economic urgency to adopt WtE due to limited landfill capacity, the current waste management policy mainly focuses on minimizing Capex and initial investment risks, making it inadequate. This narrow focus overlooks intangible benefits like improved health and neighborhood comfort. Integrating ecological and human factors is crucial for sustainable development. This research assesses the techno-economic feasibility of the Hydrodrive-Incinerator as a sustainable waste solution for Bogor City, using a comprehensive Enviro-Economic Assessment

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*e-mail: nugr004@brin.go.id
Tel.: +62-812-810-7496

to monetize benefits like public health and GHG reductions. Results indicate that if GHG emissions are not accounted for, the project is profitable in its 13th year (IDR 216,874,760). Crucially, when GHG emissions are included, profitability is accelerated to its 8th year (IDR 2,434,809,810). WtE incinerators promote sustainable waste management and environmental objectives, while also providing financial advantages. Sensitivity analysis reveals that the project's viability is highly sensitive to the valuation of Environmental Benefits, with a pessimistic combination of increased Capex (+10%) and reduced Environmental Benefit (-25%) being the only scenario that renders the project economically unfeasible (B/C Ratio 0.99). Therefore, strong local government commitment through policy and funding is paramount for successful implementation.

Keywords: cost-benefit analysis, tangible, intangible, hydrodrive-incinerator technology, sustainability

Introduction

Climate change is a critical global phenomenon characterized by rising carbon dioxide (CO_2) concentrations, altered weather patterns, and increasing sea levels [1]. This condition is driven by greenhouse gases (GHGs), including CO_2, chlorofluorocarbons (CFCs), and methane (CH_4), leading to the scarcity of clean water, reduced crop yields, and risks to human health [2]. Organic and inorganic waste require meticulous management to prevent air pollution and mitigate the spread of disease vectors. Inappropriate management of these waste streams, particularly through landfilling and open dumping, generates significant CH_4 and CO_2 emissions, establishing waste as a critical contributor to the climate crisis [3-5].

The global waste crisis is a complex and multilayered problem that goes beyond typical municipal waste management [6-8]. In Indonesia, managing Municipal Solid Waste (MSW) has become a critical issue. Data from the Ministry of Environment and Forestry (KLHK) in 2019 indicated that Indonesia generated 64 million tonnes of waste annually, of which 44.5% was transported without proper processing. Furthermore, 60% of all landfills had already reached their maximum capacity limit since 2015 [9-11]. In Bogor City, this national crisis is deeply felt, with daily waste generation surpassing capacity. While the existing regional landfill (TPA Galuga) faces imminent closure and capacity issues, there is an urgent need to adopt advanced management solutions [12-16]. Waste-to-Energy (WtE) technology, particularly thermal treatment methods like incineration, offers a viable pathway to sustainable waste management by drastically reducing waste volume while simultaneously recovering energy [17-20].

This study assesses the economic and environmental sustainability of the Hydrodrive-Incinerator technology as a waste management solution for Bogor City. The Hydrodrive-Incinerator is selected for its advanced system, which promises high efficiency and lower emissions compared to conventional thermal treatment, making it a promising option for Indonesian municipalities [21, 22]. The Hydrodrive-Incinerator technology surpasses traditional WtE limits by using fuel only during start-up, then combusting waste with superheated steam from a furnace boiler. It can eliminate waste without additional fuel, making it more cost-effective and environmentally friendly. The system features a rotary dryer, furnace boiler, and emission control systems for enhanced efficiency.

However, the successful implementation of large-scale WtE projects is often hindered by high Capital Expenditure (Capex) and challenges in demonstrating adequate return on investment based solely on financial metrics [23-25]. This financial barrier is exacerbated by a fundamental gap in current environmental policy and research: the failure to assign a comprehensive monetary value to the intangible benefits of WtE. Most current feasibility studies mainly focus on tangible costs and benefits like electricity sales and O&M costs, often neglecting the economic advantages of avoiding public health expenses, enhancing air quality, and lowering GHG emissions [26, 27]. While the exclusion results in an underestimation of the Net Present Value (NPV) and a distorted assessment of project viability, this study used a thorough Enviro-Economic Assessment with Cost-Benefit Analysis (CBA) to fully capture the monetary worth of intangible benefits, focusing on GHG emissions and public health gains. This approach helps promote sustainable development by integrating ecological and human considerations [28-30].

The aim of this research is twofold: (1) to assess the overall financial and environmental feasibility of the Hydrodrive-Incinerator WtE project in Bogor City by comparing approaches, with and without monetized intangible benefits, and (2) to offer a solid, evidence-based economic recommendation for local government policy and investment decisions to support sustainable waste management, promote circularity, and explore promising pathways to improve sustainability [31] and cost savings [32].

Materials and Methods

Data Collection

This research evaluates the application of the Hydrodrive-Incinerator technology as a waste management device in Bogor City by considering the economic and environmental impacts as benefits. The Hydrodrive-Incinerator technology results from a collaborative research project between the National Research and Innovation Agency (BRIN) and partner PT. Bumi Resik Nusantara and represents an innovation with residue characteristics that meet the quality standards for air and wastewater emissions.

This research uses primary and secondary data. Primary data were obtained through in-depth interviews with respondents, namely, WtE inventors, researchers of WtE, Bogor City Government (Regional Development Planning Agency and the Environmental Agency), waste bank management, and Temporary Shelter of Reduce, Recycle, and Reuse (TPS3R) management, and PT. Bumi Resik Nusantara. Secondary data were obtained from literature studies/reports and from the Bogor City Government, TPS3R management, and PT. Bumi Resik Nusantara.

Data Processing

This method evaluates systematically and analytically by comparing the value of benefits and costs in assessing the economic feasibility of a project. It can be called the Cost-Benefit Analysis (CBA) method [33]. The calculation was carried out in three stages: the first stage identified Capex, the second calculated Opex, and the third calculated the potential benefits arising from the operation of the Hydrodrive-Incinerator, both tangible and intangible. Tangible benefits include economic and government budget reallocation benefits, while intangible benefits include public health and environmental/GHG benefits.

The calculation in the third stage uses two approaches. The first approach considers economic and public health variables and calculates the potential tangible and intangible public health benefits. The second approach considers economic, public health, and environmental (GHG) variables and calculates the potential tangible and intangible benefits related to public health and environmental/GHG factors (Fig. 1). Both approaches consider the potential costs and benefits of sustainable waste management associated with the GHG emission inventory to support effective mitigation policies. Approach 1 represents the scenario in which the GHG emission inventory has not been calculated, while approach 2 represents the scenario in which the inventory has been calculated.

Tangible Cost of Hydrodrive-Incinerator

Capital expenditure (Capex):

Capex is calculated from the construction stage until the device is ready. Capex was represented in Eq. (1).

$$Capex : \Delta PPE - Current\ depreciation \tag{1}$$

Capex is capital expenditure, and ΔPPE is Property, Plant and Equipment Changes.

Operating expenditures (Opex):

Opex includes labor and maintenance costs so the device can function optimally. Opex was represented in Eq. (2).

$$Opex = Initial\ cost + Operational\ cost + Maintenance\ cost \tag{2}$$

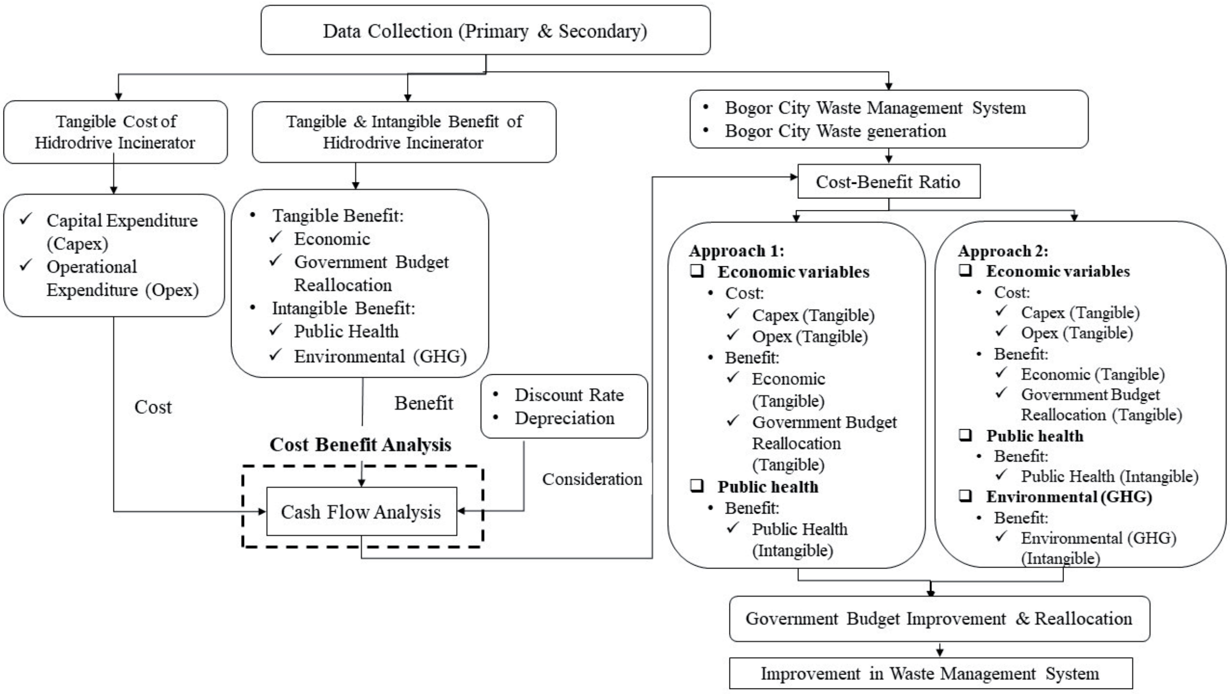

Fig. 1. Research framework.

The initial cost is the cost of investment plus interest, and the operational cost is the cost of labor, electricity, and maintenance.

Tangible and Intangible Benefits of Hydrodrive-Incinerator

Tangible economic benefit:

Residual waste can be converted into electricity using Turbine ORC technology integrated with the Hydrodrive-Incinerator. This system processes organic and inorganic waste, producing Fly Ash and Bottom Ash (FABA) as a by-product, which can be utilized in brick production for construction. The steps for calculating the amount and value of FABA are presented in Eqs. (3) and (4).

$$AF = IC \ x \ PIR \tag{3}$$

$$TFV = AF \ x \ FP \tag{4}$$

where AF is the amount of FABA, IC represents the incinerator capacitance, PIR represents the percentage of incinerator residue from the amount of waste processed, TFV represents the total FABA value, and FP denotes the FABA price.

The calculation of the profit from the electricity generated by this incinerator technology can be determined using Eq. (5):

$$ES = EG \ x \ OH \ x \ ODy \ x \ BP \tag{5}$$

where ES is the electricity sale, EG represents the electricity generated, OH denotes the incinerator's operating hours, ODy indicates the yearly operating days, and BP refers to the base price at which the national electricity company sells electricity to consumers.

Government budget reallocation benefit:

The government budget for waste management comprises two categories: capital expenditure and operational expenditure. Capital expenditure includes investment in vehicles (for collection and transportation), machinery and equipment, new projects, and infrastructure [34-36]. Meanwhile, operational costs are costs that must be incurred in daily operations for waste collection [37]. These operational costs include waste collection costs, salaries, and wages, as well as repair and maintenance costs [38]. The management of waste requires a regional government budget for the development of integrated waste processing facilities (TPST) as a form of environmental management originating from general income (local waste tax) and grant budgets [39]. Eq. (6), (7), (8), and (9) present the steps for calculating the total budget optimization potential per year.

$$AWPT = \frac{CY}{TY} \tag{6}$$

$$RBT = (AWPT \ x \ FOC) + (AWPT \ x \ MC) \tag{7}$$

$$RWT = AWPT \ x \ WTW \tag{8}$$

$$TBOP = RBT + RWT \tag{9}$$

where AWPT is the percentage of the amount of waste processed at the final processing site per year, CY represents the capacity of the Hydrodrive-Incinerator to process the waste per year, TY represents the amount of waste processed at the final processing site per year, RBT is the potential reduction in operational and maintenance budgets for transportation per year, FOC represents the fuel operational costs per year, MC represents the maintenance costs for waste transportation fleet per year, RWT is the potential reduction in wages for transportation workers, WTW represents the total wages for waste transportation workers per year, and TBOP represents the total budget optimization potential per year.

Intangible public health benefit:

Health compensation depends on the Hydrodrive-Incinerator capacity that can be processed, the number of trips per day, and the cost of each trip. The larger the Hydrodrive-Incinerator capacity, the more waste can be managed so that the negative impact of waste on health is lower. The health compensation was determined using Eq. (10):

$$HC = \frac{CA}{TR} x \ AT \ x \ CT \tag{10}$$

where HC denotes the health compensation provided, CA represents the capacity of the Hydrodrive-Incinerator to process the waste per day, TR represents the total waste per day, AT represents the number of trips per day, and CT represents the cost of each trip.

Intangible environmental benefit:

The carbon market is a market mechanism considered capable of reducing carbon emissions. When the Bogor City government invests in Hydrodrive-Incinerator waste processing technology, the estimated economic value of emissions based on the IPCC Guidelines for National Greenhouse Gas Inventories [40] can be calculated as follows (see Eq. (11)).

$$E = AD \ x \ EF \tag{11}$$

where E is representative of GHG emissions, AD represents the waste activity data, and EF represents the emission factor.

Cost-benefit ratio:

In determining the consistency of cost-benefit value calculations, the WtE device is assumed to operate with a waste input capacity of 30 tons per day, with an operational working time of 15 hours per day for 365 working days (The Hydrodrive-Incinerator has a capacity of 2 tons per hour. With 15 hours of operation, the Hydrodrive-Incinerator can process up to 30 tons of

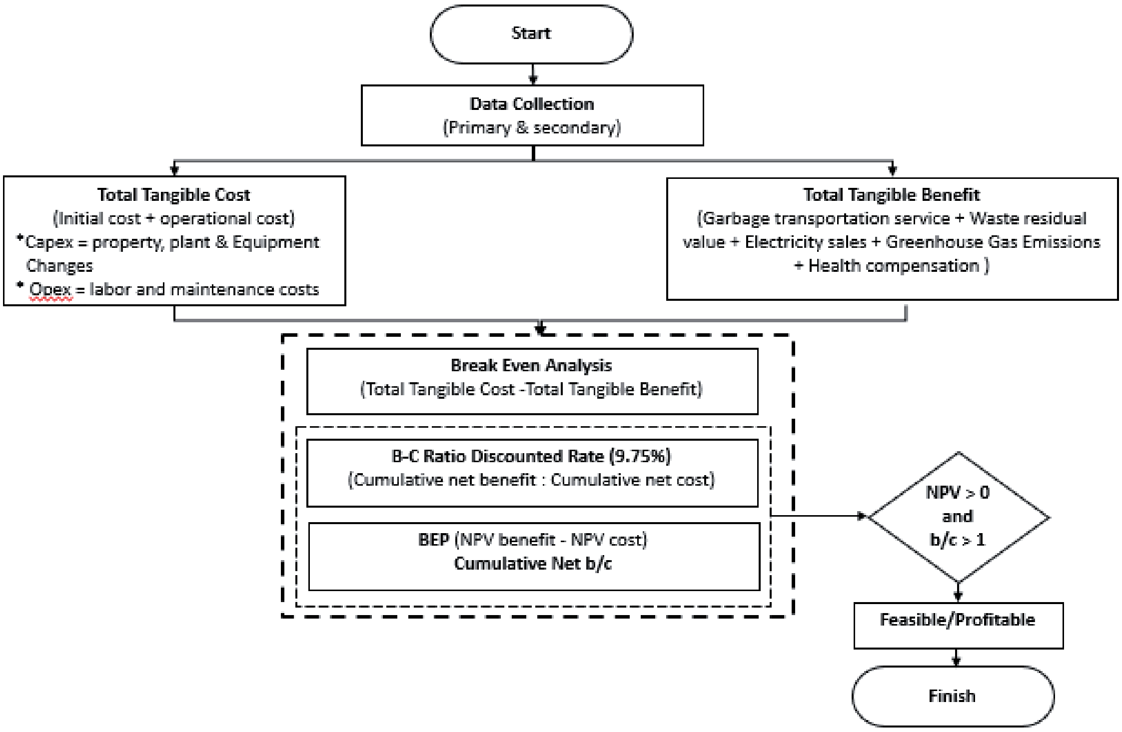

Fig. 2. Flow diagram for the CBA process.

waste per day). Additionally, this study calculated a CBA projecting a project life of 10 years. The assumption of a 10-year calculation is straight-line according to project age, so the economic value is up to 10 years before major servicing. CBA is a tool for evaluating profits or losses from investments by considering the period of the investment, including the discount value and uncertainty value [41, 42]. Apart from that, CBA is also a method for evaluating the value of a project by comparing the overall value of the costs and benefits of the project. This analysis can analyze intangible benefits, such as environmental and health aspects. When the Net Present Value (NPV) is greater than zero, and the B/C ratio is greater than 1, the activity is economically feasible/profitable (Fig. 2) [42-44].

The benefit-cost ratio formula is outlined below (see Eq. (12)).

$$Benefit\ Cost\ Ratio = \frac{\sum_{t=0}^{n} \frac{CF_t[Benefits]}{(1+i)^t}}{\sum_{t=0}^{n} \frac{CF_t[Costs]}{(1+i)^t}} \tag{12}$$

where the CF of the project is cash flow, i is the discount rate, n is the number of periods, and t is the operating period in which the cash flow occurs.

NPV can be used to assess the viability of investments by considering both Capex and Opex. When the Net Present Value (NPV) exceeds zero, and the B/C exceeds 1, the activity is economically feasible/profitable. The calculation of NPV is shown in Eq. (13).

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+i)^t} - I_0 \tag{13}$$

Where *NPV* represents the project's *NPV*, CF_t represents net cash flow in period t, I_0 is the initial investment, i represents the discount rate, t is the time period (year-t), and n is the project age.

Results and Discussion

Waste management in Bogor is still conventional. The government has implemented a Composting program, a Temporary Shelter of 3R (Reduce, Recycle, Reuse) (TPS3R), an Integrated Waste Management Site (TPST), and waste banks [45]. In addition, 74.72% of the total waste is managed through waste transportation services in the community and then transported to the landfill. Waste management has value for the environment and economy through implementing a zero-waste culture and the 3R principle [46-49].

Tangible Cost of Hydrodrive-Incinerator

The total cost of the incinerator consists of Capex and Opex (Table 1). The costs used in this research only take into account tangible costs. The capital expenditure for using the Hydrodrive-Incinerator offered by the private sector to the government is IDR 30,000,000,000.00. Capex does not include land value because regional

Table 1. Potential total tangible costs from using Hydrodrive-Incinerator technology in Bogor City (in IDR 000).

Year	Tangible Cost (in IDR 000)		
	Initial Cost	Operational Cost	Total Cost
1	6,000,000.00	1,935,000.00	7,935,000.00
2	6,300,000.00	1,993,050.00	8,293,050.00
3	6,315,000.00	2,052,841.50	8,367,841.50
4	6,315,750.00	2,114,426.75	8,430,176.75
5	6,315,787.50	2,177,859.55	8,493,647.05
6	-	2,243,195.33	2,243,195.33
7	-	2,310,491.19	2,310,491.19
8	-	2,379,805.93	2,379,805.93

governments procure products for the public interest by utilizing regional government land ownership.

Meanwhile, operational costs include labor, starter fuel, water supply, wheel loader fuel, electricity, equipment, and maintenance, amounting to IDR 1,935,000,000.00 per year. This research assumed that the incinerator purchase would be carried out in stages over 5 years, with an interest of 5% per year and an increase in operational costs of 3% per year. Table 1 outlines a breakdown of the calculations per year.

Tangible and Intangible Benefits of Hydrodrive-Incinerator

Tangible Economic Benefit

The economic benefits estimate includes the value generated by circular economy activities and the potential value of electricity sales generated by the Hydrodrive-Incinerator device. Hydrodrive-Incinerator technology can be integrated with an electric generator to produce electricity from waste. It terminates residual waste as well as organic and inorganic waste. This process will produce residue in the form of 3% Fly Ash and Bottom Ash (FABA), which can be used to make bricks and build wall structures.

The source of waste material comes from residual waste from all TPS3R in Bogor, with a capacity of 8 tons/day, and unmanaged waste in Bogor, equivalent to 28.23 tons/day or 3.75% of Bogor's total daily waste produced. The capacity of the Hydrodrive-Incinerator technology to process waste is 30 tons/day, and it operates 365 days. Therefore, the incinerators have the potential to operate in Bogor City. With an IDR 525 thousand per ton sales value, 328.5 tons of FABA can be produced annually, resulting in a total value of IDR 172.462 million.

Efforts to address climate change and energy supply security require increased use of domestic and low-carbon energy sources [26]. Currently, most electricity sources come from burning coal, which hurts the environment. Since 2017, investment in renewable energy generation has stagnated, and in the last two years, this investment is still far from the government's target [50]. Indonesia has a target that new and renewable energy will be increased to 23% in 2025 from 5% in 2013.

The Hydrodrive-Incinerator technology device installed on the waste processing incinerator will produce 100 kWh of electricity per hour from the hot air from burning waste. If calculated by the selling price of electricity produced by the State Electricity Company (PLN) in Indonesia, it is IDR 1,700/kWh, then in 1 year (365 days and daily operation is 15 hours), the incinerator device with Hydrodrive-Incinerator technology can generate income of IDR 930,750,000. This income assumes that the incinerator manager uses the electricity generated to reduce operational electricity costs and uses it as the source of electricity around the incinerator area. Electricity generated from the Hydrodrive-Incinerator technology device at the incinerator can also be used as a source of electricity for street lighting or electricity-based vehicle charging devices owned by the local government.

Government Budget Reallocation Benefit

Based on the Bogor City Environmental Service Report for 2022, the Regional Waste Management and System Development Program and the Waste Management Program are part of the strategic target to improve waste services in Bogor City. The waste service budget is 34.1% of the budget allocation for the Bogor City Environmental Service. In 2022, the Bogor City Government will incur operational costs (fuel) and maintenance of waste transportation equipment amounting to IDR 10,211,352,000, while the cost of maintaining the waste transportation fleet in 2022 is IDR 3,917,395,350. Incinerators can reduce waste in Bogor City. The potential waste reduction from implementing the Hydrodrive-Incinerator is 10,950 tons per year, or 5.45% of the amount of waste produced in Bogor City, namely 200,750 tons per year in 2020 (Waste Management Balance for 2021-2022 Bogor City).

By implementing a Hydrodrive-Incinerator, the potential for reallocating the operational cost budget for fuel is IDR 556,982,836.36, while the potential reallocation of transport fleet maintenance costs could be IDR 21,676,110. From the aspect of waste management labor expenditure, Bogor City is providing financing for the wages of waste transport workers in 2022, amounting to IDR 41,099,940,000. By implementing a Hydrodrive-Incinerator device, which has the potential to reduce waste by 5.45%, labor wages can be saved up to IDR 2,239,946,730. Thus, the total budget for waste transportation services can potentially be optimized to be as much as IDR 3,010,605,680.

Intangible Public Health Benefit

Calculating environmental impact involves assessing the amount of GHG emissions and considering the economic effects of waste emissions. It also involves taking into account the compensation provided by the government to communities living near the waste processing site for any health issues. People living around the landfill are at risk of experiencing health problems. This is because landfill urban waste can be a source of pollution in the surrounding environment [51]. Environmental impacts are chemical pollutants such as heavy metals, methane gas, H_2S, CO, and microorganisms in the form of bacteria. This shock can cause health effects such as skin irritation, eye irritation, gastrointestinal tract disorders, allergies, nose irritation, and other symptoms, and there is also a risk of cancer [52].

Health compensation in this research is assumed to be the operational costs incurred in waste management because waste management through a Hydrodrive-Incinerator can reduce the negative impact of waste on the health of the surrounding community. Operational costs depend on the Hydrodrive-Incinerator capacity, the number of trips, and the cost of trips. Based on the survey results, the Hydrodrive-Incinerator capacity is 30 tons or only 5.45% of the total waste, the average daily transportation to the TPA is 130 trips, and the cost of each trip is IDR 35,000. Therefore, the health compensation that can be given is IDR 245,000 per day or IDR 89,425,000 per year.

Intangible Environmental Benefit

One of the causes of climate change is waste. MSW is not only a problem for developing countries; developed countries also experience waste problems. Waste increases along with the rise in living standards, so waste disposal becomes difficult. Collecting waste, landfilling, and burning triggers a decline in environmental quality and an increase in GHG emissions [53, 54]. Illegal and uncontrolled open rubbish dumps can release pollutants into the environment. For example, open burning of waste can release pollutants into the atmosphere, such as carbon monoxide (CO) and nitrogen oxides (NO_x) [2]. Research in Switzerland for the period 1990-2017 shows that total MSW causes GHG emissions from the waste

Table 2. Approach 1 – Potential total benefits of Hydrodrive-Incinerator technology in Bogor City considering economic and public health variables (in IDR 000).

Year	Potential Total Benefits Considering Economic and Public Health Variables (in IDR 000)				
	Total FABA Value	Electricity Sales	Total Budget Optimization Potential	Health Compensation	Total Benefits
1	172,462.00	930,750.00	3,010,605.68	89,425.00	4,203,243.68
2	175,911.24	949,365.00	3,070,816.82	91,213.50	4,287,306.56
3	179,429.46	968,352.30	3,132,233.16	93,037.77	4,373,052.70
4	183,018.05	987,719.35	3,194,877.82	94,898.53	4,460,513.75
5	186,678.42	1,007,473.73	3,258,775.38	96,796.50	4,549,724.02
6	190,411.98	1,027,623.21	3,323,950.89	98,732.43	4,640,718.51
7	194,220.22	1,048,175.67	3,390,429.91	100,707.07	4,733,532.88
8	198,104.63	1,069,139.19	3,458,238.50	102,721.22	4,828,203.53
9	202,066.72	1,090,521.97	3,527,403.27	104,775.64	4,924,767.60
10	206,108.05	1,112,332.41	3,597,951.34	106,871.15	5,023,262.96
11	210,230.22	1,134,579.06	3,669,910.37	109,008.58	5,123,728.21
12	214,434.82	1,157,270.64	3,743,308.57	111,188.75	5,226,202.78
13	218,723.52	1,180,416.05	3,818,174.75	113,412.52	5,330,726.83

Table 3. Approach 1 – Break-even analysis of Hydrodrive-Incinerator technology in Bogor City considering economic and public health variables (in IDR 000).

Year	Break-Even Analysis										
	Break-Even Analysis (B-C)	Cumulative benefits	Cumulative cost	B-C before Discoun-ted Rate	NPV Benefit (9.75%)	NPV Cost (9.75%)	Cumulative net benefit	Cumulative net cost	B-C Ratio Discoun-ted Rate	BEP	Net b/c
1	-3,731,758.27				3,829,833.01	7,230,068.34				-3,400,235.33	-3,400,235.33
2	-4,005,743.44	8,490,548.29	16,228,050.00	0.52	3,906,429.67	7,556,309.79	7,736,262.68	14,786,378.13	0.52	-3,649,880.12	-7,050,115.45
3	-3,994,788.80	12,863,600.99	24,595,891.50	0.52	3,984,558.27	7,624,456.95	7,890,987.94	15,180,766.74	0.52	-3,639,898.68	-10,690,014.13
4	-3,969,663.00	17,324,114.74	33,026,068.25	0.52	4,064,249.43	7,681,254.44	8,048,807.70	15,305,711.38	0.53	-3,617,005.01	-14,307,019.14
5	-3,943,923.02	21,873,838.77	41,519,715.29	0.53	4,145,534.42	7,739,086.15	8,209,783.85	15,420,340.59	0.53	-3,593,551.73	-17,900,570.87
6	2,397,523.17	26,514,557.27	43,762,910.63	0.61	4,228,445.11	2,043,913.74	8,373,979.53	9,782,999.89	0.86	2,184,531.36	-15,716,039.50
7	2,423,041.68	31,248,090.15	46,073,401.82	0.68	4,313,014.01	2,105,231.16	8,541,459.12	4,149,144.90	2.06	2,207,782.85	-13,508,256.65
8	2,448,397.60	36,076,293.68	48,453,207.75	0.74	4,399,274.29	2,168,388.09	8,712,288.30	4,273,619.25	2.04	2,230,886.20	-11,277,370.45
9	2,473,567.50	41,001,061.28	50,904,407.86	0.81	4,487,259.78	2,233,439.73	8,886,534.07	4,401,827.82	2.02	2,253,820.04	-9,023,550.41
10	2,498,526.84	46,024,324.24	53,429,143.97	0.86	4,577,004.97	2,300,442.93	9,064,264.75	4,533,882.66	2.00	2,276,562.05	-6,746,988.36
11	2,523,250.02	51,148,052.45	56,029,622.16	0.91	4,668,545.07	2,369,456.21	9,245,550.04	4,669,899.14	1.98	2,299,088.86	-4,447,899.51
12	2,547,710.24	56,374,255.23	58,708,114.70	0.96	4,761,915.97	2,440,539.90	9,430,461.04	4,809,996.11	1.96	2,321,376.07	-2,126,523.43
13	2,571,879.52	61,704,982.07	61,466,962.02	1.00	4,857,154.29	2,513,756.10	9,619,070.26	4,954,296.00	1.94	2,343,398.19	216,874.76

sector, and recycling and composting waste processing can reduce GHG emissions [53].

One way to reduce GHG is to set emissions prices. When emissions resulting from waste are assessed economically, economic actors try to invest in environmentally friendly technology. The government, through Government Regulation Number 98 of 2021, can collect carbon on goods and services that have the potential to produce emissions, one of which is waste and is strengthened by Law Number 4 of 2023 concerning the Development and Strengthening of the Financial Sector through Financial Services Authority Regulation Number 14 of 2023 concerning Carbon Trading through the Carbon Exchange.

Hydrodrive-Incinerator technology is used 365 days for 1 year, producing emissions of 4,675.65 tons of CO_2e/year. The Rupiah exchange rate is IDR 15,000, the emission factor for waste is 0.427 Kg CO_2/Kg [55], the Hydrodrive-Incinerator technology capacity per day is 30 tons, and the carbon price per day is USD 25 [56]. The economic value of emissions from Hydrodrive-Incinerator technology investment is IDR 1,753,368,750/year. When the Bogor City Government invests in Hydrodrive-Incinerator technology, it has the potential to have economic benefits from emissions of IDR 1,753,368,750/year.

Cost-Benefit Ratio

Calculations are carried out using two approaches. The first approach considers economic and public health variables, and the second considers economic and public health variables and environmental variables (GHG).

Approach 1:

This approach calculates the benefit value of a turbine hydro-drive incinerator, which comes from total FABA value, electricity sales, total budget optimization potential from budget reductions in waste transportation services, and health compensation.

The residual value of waste in year 1 was IDR 172,462,000, the value of electricity sales in year 1 was IDR 930,750,000, the value of budget optimization potential in year 1 was IDR 3,010,605,680, and the value of health compensation in year 1 was IDR 89,425,000. Waste residual value, electricity sales, budget optimization potential, and health compensation are assumed to increase by 3% per year. A description of the calculation of tangible benefits is provided up to the 13th year.

After analyzing potential total tangible costs (Table 1) and total benefits considering economic and public health variables (Table 2), the researchers calculated BC. The calculation uses a discounted rate of 9.75% as the assumption (these assumptions are based on the values used in similar feasibility studies in Indonesia for infrastructure and energy projects). The calculations per year are described in Table 3, showing the results of the BC ratio analysis where the BC ratio value >1 occurs in year 7. This indicates that the capital and operational expenditures for procuring the Hydrodrive-Incinerator have been paid off but have not provided a profit. Investing in this tool will benefit the 13th year, where net b/c has shown a positive value.

Based on approach 1, the break-even point for the Hydrodrive-Incinerator technology in Bogor City is achieved in the 7th year (Table 3). At this stage, the cumulative tangible benefits are approximately IDR. 31,248,090.15 surpass the cumulative costs of about IDR. 46,073,401.82. The Break-Even Analysis (B-C) indicates a value of IDR. 2,397,523.17, highlighting the year when the project's financial returns exceeded its expenditures. Notably, the B-C ratio before applying the discount rate is 0.68 in this 7th year, signifying that the project's benefits are gradually catching up with

Table 4. Approach 2 – Potential total benefits of Hydrodrive-Incinerator technology in Bogor City considering economic, public health, and environmental (GHG) variables (in IDR 000).

Year	Potential Total Benefits Considering Economic, Public Health, and Environmental Variables (in IDR 000)					
	Total FABA Value	Electricity Sales	Total Budget Optimization Potential	Health Compensation	GHG Emissions	Total Benefits
1	172,462.00	930,750.00	3,010,605.68	89,425.00	1,753,368.75	5,956,611.43
2	175,911.24	949,365.00	3,070,816.82	91,213.50	1,788,436.13	6,075,743.65
3	179,429.46	968,352.30	3,132,233.16	93,037.77	1,824,204.85	6,197,258.53
4	183,018.05	987,719.35	3,194,877.82	94,898.53	1,860,688.94	6,321,203.70
5	186,678.42	1,007,473.73	3,258,775.38	96,796.50	1,897,902.72	6,447,627.77
6	190,411.98	1,027,623.21	3,323,950.89	98,732.43	1,935,860.78	6,576,580.33
7	194,220.22	1,048,175.67	3,390,429.91	100,707.07	1,974,577.99	6,708,111.93
8	198,104.63	1,069,139.19	3,458,238.50	102,721.22	2,014,069.55	6,842,274.17
9	202,066.72	1,090,521.97	3,527,403.27	104,775.64	2,054,350.94	6,979,119.66
10	206,108.05	1,112,332.41	3,597,951.34	106,871.15	2,095,437.96	7,118,702.05

the costs even before considering the time value of money. As the project progresses beyond this point, the economic viability is further reinforced, with benefits continuing to rise relative to costs, ultimately validating the long-term sustainability of the technology.

Approach 2:

In contrast to approach 1, which calculates the benefit value from total FABA value, electricity sales, total budget optimization potential from budget reductions in waste transportation services, and health compensation. Approach 2 considers environmental (GHG) variables. The value of GHG in year 1 was IDR 1,753,368,750. Table 4 analyzes tangible costs, tangible benefits, and intangible benefits up to the 10th year.

The assumptions used are the same as in the first approach. Namely, the discount rate is 3%, and the PV is 9.75%. Based on calculations, the investment in the Hydrodrive-Incinerator was paid off in the 6th year, where the BC ratio calculation was >1. Furthermore, in the 8th year, the net b/c has shown a positive value, meaning that this year, the investment was made back (starting to make a profit). This indicates that the analysis by including the value of intangible benefits (compensation for environmental value) will obtain a faster profit level.

Based on approach 2, the break-even point for the Hydrodrive-Incinerator technology in Bogor City (Table 5) is reached in the seventh to 8th year. At this juncture, the analysis indicates that the cumulative benefits have exceeded the cumulative costs, with the Break-Even Analysis (B-C) value amounting to IDR 4,397,620.74. This positive net benefit reflects the financial viability of the technology, showcasing that the total benefits accrued over the 7 years surpass the initial and ongoing costs. At this point, the B-C Ratio Discounted Rate stands at 0.96, signifying that the benefits, even when discounted at 9.75%, slightly lag behind the costs. However, the Net Present Value (NPV) analysis reveals a different picture, with the NPV of benefits and costs amounting to IDR 2,105,231.16, further affirming the economic potential of the incinerator technology by yielding a cumulative net benefit of IDR 12,104,503.20 against a cumulative net cost of IDR 4,149,144.90.

Sensitivity Analysis

To assess financial robustness and project risks associated with uncertainties in key parameters, a comprehensive sensitivity analysis was conducted. This analysis examines how variations in three critical input variables, Capex, Environmental Benefit, and Operational Downtime, impact the project's viability metrics, specifically NPV and BEP.

Impact of Capex and Environmental Benefit

This analysis assesses the impact of external financial and policy uncertainties on the project's profitability.

Table 5. Approach 2 - Break-Even analysis of Hydrodrive-Incinerator Technology in Bogor City considering economic, public health, and environmental variables (in IDR 000).

Year	Break-Even Analysis										
	Break-Even Analysis (B-C)	Cumulative benefits	Cumulative cost	B-C before Dis-counted Rate	NPV Benefit (9.75%)	NPV Cost (9.75%)	Cumulative net benefit	Cumulative net cost	B-C Ratio Discounted Rate	BEP	Net b/c
1	-1,978,388.57				5,427,436.38	7,230,068.34				-1,802,631.96	-1,802,631.96
2	-2,217,306.35	12,032,355.08	16,228,050.00	0.74	5,535,985.11	7,556,309.79	10,963,421.49	14,786,378.13	0.74	-2,020,324.69	-3,822,956.65
3	-2,170,582.97	18,229,613.61	24,595,891.50	0.74	5,646,704.81	7,624,456.95	11,182,689.92	15,180,766.74	0.74	-1,977,752.14	-5,800,708.78
4	-2,108,973.05	24,550,817.31	33,026,068.25	0.74	5,759,638.91	7,681,254.44	11,406,343.71	15,305,711.38	0.75	-1,921,615.53	-7,722,324.32
5	-2,046,019.27	30,998,445.08	41,519,715.29	0.75	5,874,831.68	7,739,086.15	11,634,470.59	15,420,340.59	0.75	-1,864,254.46	-9,586,578.78
6	4,333,384.99	37,575,025.41	43,762,910.63	0.86	5,992,328.32	2,043,913.74	11,867,160.00	9,782,999.89	1.21	3,948,414.57	-5,638,164.21
7	4,397,620.74	44,283,137.34	46,073,401.82	0.96	6,112,174.88	2,105,231.16	12,104,503.20	4,149,144.90	2.92	4,006,943.73	-1,631,220.48
8	4,462,468.24	51,125,411.52	48,453,207.75	1.06	6,234,418.38	2,168,388.09	12,346,593.26	4,273,619.25	2.89	4,066,030.29	2,434,809.81
9	4,527,919.55	58,104,531.17	50,904,407.86	1.14	6,359,106.75	2,233,439.73	12,593,525.13	4,401,827.82	2.86	4,125,667.02	6,560,476.83
10	4,593,965.94	65,223,233.22	53,429,143.97	1.22	6,486,288.88	2,300,442.93	12,845,395.63	4,533,882.66	2.83	4,185,845.96	10,746,322.78

Scenarios were tested by applying a ±10% variation to Capex and a ±25% variation to the Environmental Benefit, compared to the Base Case.

The results in Table 6 indicate that the project's financial viability is highly sensitive to the combination of reduced environmental revenue and increased capital costs. The results above reveal two critical findings. First, while the project exhibits a negative NPV across most scenarios, its Base Case B/C Ratio of 1.21 confirms the overall economic and social viability of the project (Benefits > Costs) when environmental externalities are internalized. Second, financial viability is highly sensitive to adverse changes. The most sensitive variable in isolation, causing the most significant NPV reduction, is Pessimistic II (-25% Environmental Benefit), which shifts the Break-Even Point (BEP) from year 6 to year 7. Crucially, the Pessimistic Combination scenario (+10% Capex and -25% Environmental Benefit) causes the most detrimental shift, resulting in a B/C ratio of 0.99. This is the only scenario where the project is deemed economically unfeasible (B/C<1.0), emphasizing the need to mitigate both capital risk and fluctuations in environmental revenue valuation. Conversely, the Optimistic II scenario, involving a 25% increase in Environmental Benefit, yields the highest B/C ratio (1.52) and brings the NPV closest to zero (-5,728.00 million IDR).

The sensitivity results are visualized in Fig. 3, which shows the order of variables most affecting the project's NPV. The one-way analysis indicates that the Environmental Benefit, with a 25% variation, has the widest impact range on the NPV, making it the most sensitive variable. It is followed by Capex, with a 10% variation. This highlights that the project's economic viability heavily depends on environmental incentives, even more than on the initial investment costs.

Risk of Operational Downtime

This analysis evaluates the financial impact of decreased operating capacity caused by unscheduled maintenance or system failures. Table 7 displays the risk scenarios for operational downtime. The base operating time is assumed to be 7,920 hours per year. This scenario examines a 5% and 10% reduction in annual operating hours.

For this particular sensitivity test, a simplified cost assumption is used. Fixed Operating and Maintenance (O&M) Costs stay constant, while Variable O&M Costs decrease proportionally with fewer operating hours. Notably, any potential additional costs resulting from failures – such as emergency repairs or penalties for alternative waste disposal – are excluded, allowing a focus solely on how capacity reduction affects project revenue.

Operational Downtime clearly erodes project profitability, even under the simplified cost assumption. A Minor Downtime of 5% results in an NPV reduction to -23,286.94 million IDR and a B/C Ratio of 1.15. The Significant Downtime scenario further highlights the operational risk, reducing the B/C Ratio to 1.09 and causing an NPV decrease to -26,308.90 million IDR. This demonstrates that operational reliability (Reliability, Availability, and Maintainability/RAM) is paramount; even modest increases in downtime severely erode the projected financial viability by proportionally reducing both electricity sales revenue and environmental benefits. Mitigation strategies, such as robust predictive maintenance and efficient spare parts inventory, are essential to maintain the projected cash flow.

Limitations and Future Research Directions

The Techno-Environmental-Economic Assessment of the Hydrodrive-Incinerator was conducted to evaluate the feasibility of implementing a waste incineration technology based on the Hydrodrive system, from technical, environmental, and economic perspectives. From a technical perspective, this research covers variables such as waste processing capacity and the conversion of steam to electricity through the ORC cycle or the Hydrodrive system. The environmental perspective includes variables such as total CO_2 production, the amount of solid residue (FABA), and potential health compensation. From a revenue and economic benefit perspective, this research includes variables such as Capex, Opex, potential revenue

Table 6. Sensitivity analysis scenarios and results.

Scenario	Capex Variation	Environmental Variation	Project NPV (million IDR)	B/C Ratio	Break-Even Point (Year)
Base Case	0%	0%	-20,264.99	1.21	6
Optimistic I	-10%	0%	-13,549.52	1.35	6
Pessimistic I	+10%	0%	-28,335.41	1.10	6
Optimistic II	0%	+25%	-5,155.20	1.52	6
Pessimistic II	0%	-25%	-35,374.77	2.19	7
Pessimistic Combination	+10%	-25%	-43,445.20	1.99	7

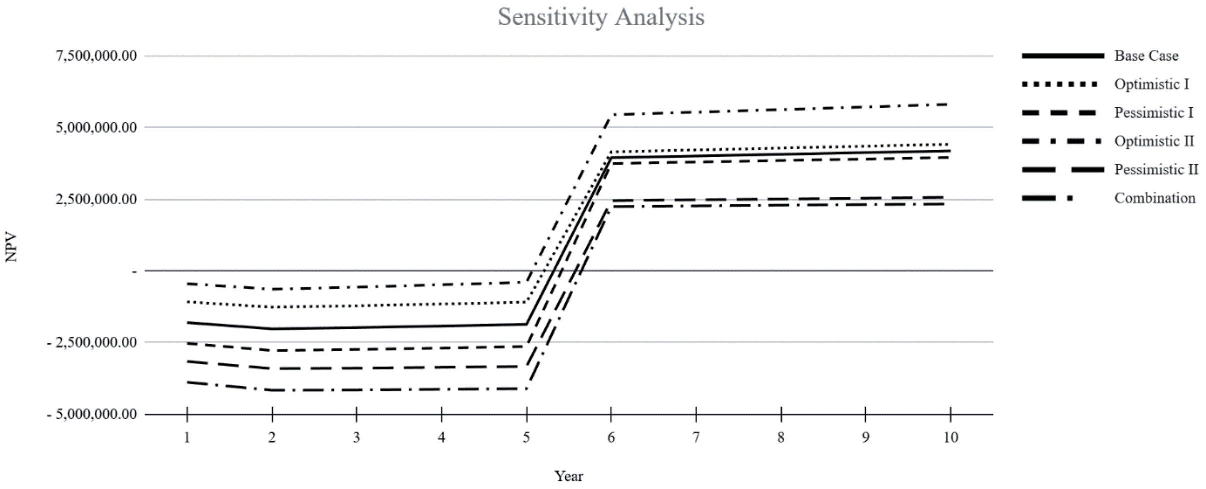

Fig. 3 Sensitivity analysis graphic.

Table 7. Risk of operational downtime scenarios and results.

Scenario	Reduction in Operating Hours	Total Operating Time (Hours/Year)	Impact on NPV (million IDR)	B/C Ratio
Base Case	0%	7,920	-20,264.99	-
Minor Downtime	5%	7,524	-23,286.94	1.15
Significant Downtime	10%	7,128	-26,308.90	1.09

from electricity sales, potential income from ash or residue utilization, potential reallocation of operational cost budget for waste transportation fuel, potential reallocation of waste transportation fleet maintenance costs, and financial analysis results (NPV, IRR) to assess whether the project is profitable in the long term. This research did not consider local social or operational factors that could shorten the device's life. The analysis did not account for uncertainty related to future changes in energy policy, electricity subsidies, or emission standards.

Thus, techno-enviro-economic assessments provide a strong scientific basis and quantitative data for designing modern waste management systems that are efficient, sustainable, and environmentally sound. Future research could address appropriate forms of collaboration among local governments, the central government, and the private sector in accordance with existing regulations.

Conclusions

Hydrodrive-Incinerator technology is the perfect solution for Bogor City, which has limited land and lacks adequate waste disposal facilities. Besides addressing waste management, this technology can be implemented as a WtE plant. The implementation of the Hydrodrive-Incinerator requires calculating the costs and benefits.

Based on environmental techno-economic analysis, two approaches were used. The first approach results show that the first investment approach was paid off in the 7th year; however, the profit obtained in the 13th year was IDR 216,874,760. In the second approach, the incinerator can obtain profits faster in the 8th year with IDR 2,434,809,810 as net profit.

The research is limited to calculating the incinerator's cost and benefit value components. Future research is suggested to include variable costs for communities near waste disposal sites that are also affected by pollution and other indicators in the cost and benefit value components.

Hydrodrive-Incinerator technology requires a high capital expenditure. Despite its cost, this technology can improve environmental quality. Therefore, government support is essential for creating a sustainable environment. The government can provide public facilities through the central government budget, regional governments, or collaboration with the private sector. The results of these techno-economic calculations can be used as input for policy formulation and as best practices for other cities.

Acknowledgments

The authors are grateful to the National Research and Innovation Agency (BRIN), through the Rumah

Program Energi Baru, for supporting the implementation of this study activity. The authors also thank the Regional Development Planning Agency and the Environment Agency of Bogor City for the data, information, and discussion.

Conflict of Interest

The authors declare no conflict of interest.

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