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Sustainable investment feasibility and optimization strategies for PLTSA Benowo: A system thinking approach

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ABSTRAK

Penelitian ini bertujuan menganalisis keberlanjutan investasi dan strategi optimalisasi operasional PLTSa Benowo di Surabaya dengan pendekatan System Thinking melalui Causal Loop Diagram (CLD) dan Cost-Benefit Analysis (CBA). Data diperoleh melalui mixed methods berupa wawancara semi-terstruktur dengan PT Sumber Organik, Dinas Lingkungan Hidup, PT PLN, Dewan Energi Nasional, serta pakar akademik di bidang keuangan, kesehatan, pengelolaan sampah, dan system thinking. Data sekunder meliputi kapasitas pengolahan sampah, volume listrik, pendapatan tipping fee dan penjualan listrik, serta biaya operasional, diambil dari laporan resmi, publikasi akademik, Bappenas, KLHK, Dinas Kependudukan Surabaya, dan Kominfo Jatim, dengan periode 2015–2023 serta proyeksi hingga 2032. Hasil CLD menunjukkan interaksi dinamis antara kualitas sampah, partisipasi masyarakat, efisiensi teknologi, dukungan kebijakan, dan dampak lingkungan. Analisis finansial menunjukkan PLTSa Benowo layak secara ekonomi, dengan BCR sebesar 2,58 pada kapasitas desain dan 1,83 pada kapasitas efektif, serta ROI sebesar 157,7% dan 83,1%. Analisis sensitivitas menunjukkan kenaikan biaya operasional dan penghapusan tipping fee menurunkan BCR dan ROI. Oleh karena itu, diperlukan efisiensi biaya, peningkatan teknologi, diversifikasi pendapatan, dan dukungan kebijakan berkelanjutan untuk menjaga kelayakan jangka panjang proyek waste-to-energy di negara berkembang.

ABSTRACT

This study aims to analyze the sustainability of investments and operational optimization strategies for the Benowo Waste-to-Energy Power Plant (PLTSa) in Surabaya using a System Thinking approach through Causal Loop Diagram (CLD) and Cost-Benefit Analysis (CBA). Data were obtained through a mixed-methods approach, combining semi-structured interviews

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with PT Sumber Organik, the Surabaya Environmental Agency, PT PLN, the National Energy Council, and academic experts in finance, health, waste management, and system thinking. Secondary data, including waste processing capacity, electricity output, tipping fee and electricity sales revenue, and operational costs, were collected from official reports, academic publications, Bappenas, the Ministry of Environment and Forestry, Surabaya Population Agency, and Kominfo Jatim, covering the period 2015–2023 with projections up to 2032. The CLD highlights dynamic interactions among waste quality, public participation, technological efficiency, policy support, and environmental impacts. Financial analysis indicates that PLTSa Benowo is economically feasible, with a Benefit-Cost Ratio (BCR) of 2.58 at design capacity and 1.83 at effective capacity, and a Return on Investment (ROI) of 157.7% and 83.1%, respectively. Sensitivity analysis shows that increases in operational costs and the removal of tipping fees reduce BCR and ROI values. Therefore, cost efficiency, technology upgrading, revenue diversification, and sustainable policy support are needed to maintain the long-term viability of waste-to-energy projects in developing countries.

INTRODUCTION

The issue of unprocessed waste in Indonesia presents a critical environmental challenge, as only around 65% of waste is properly managed, leaving approximately 35% untreated. This untreated waste significantly contributes to environmental degradation, including air and water pollution, the spread of diseases, and the emission of methane (CH_4), a potent greenhouse gas with a global warming potential 28 times higher than carbon dioxide (CO_2). Methane emissions from landfill sites account for approximately 58% of total methane emissions in ASEAN, positioning Indonesia as a major contributor to regional climate change concerns. The substantial impact includes increased greenhouse gas emissions, which exacerbate global warming, alongside the contamination of soil and water sources, threatening biodiversity and human health (Velenturf & Purnell, 2017). These challenges highlight the urgency of developing sustainable solutions such as Waste-to-Energy (WtE) technologies to reduce landfill dependency and utilize waste as a renewable energy source. Globally, waste generation has become one of the most pressing environmental concerns (Seay, 2022), as volumes continue to increase each year, driven by population growth and urbanization (Kumar & Samadder, 2017). This waste includes various types, such as plastic, household, industrial, and others, posing complex management challenges.

Indonesia, with a population of over 280 million - the fourth largest in the world faces severe waste management issues due to the high volume of waste produced relative to its capacity (Kudrna et al., 2022) -. According to data from the Ministry of Environment and Forestry (KLHK), total waste generation in Indonesia reached 13.68

million tons per year in 2023, comprising mostly organic waste (40.8%), followed by plastic, wood, paper, and other materials. However, limited infrastructure and ineffective waste segregation result in a substantial portion of waste remaining unprocessed, further exacerbating environmental and health risks (UNEP, 2024).

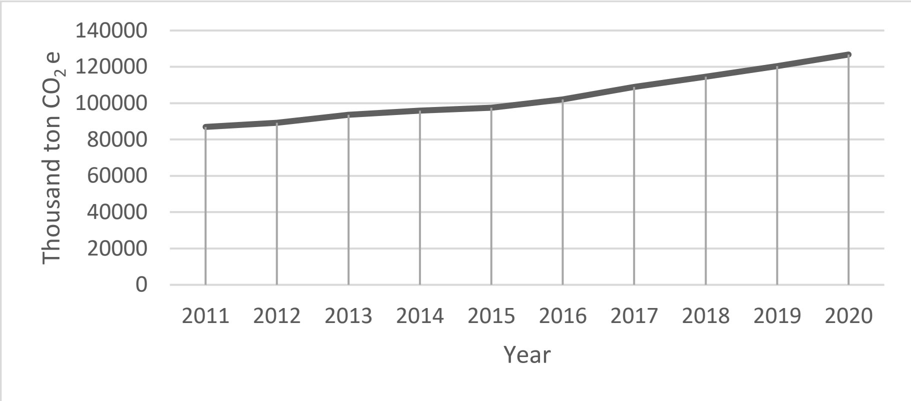

Figure 1
The trend of increasing greenhouse gases originating from waste in Indonesia

Empirical gaps exist in the limited integration of waste reduction strategies and renewable energy generation in Waste-to-Energy (WtE) projects, particularly in developing countries like Indonesia, where studies often examine these aspects in isolation without addressing systemic interactions among key factors such as waste quality, policy support, and technology efficiency. While the Indonesian government has initiated policies such as Law No. 18 of 2008 on Waste Management and Presidential Regulation No. 35 of 2018 to promote Waste-to-Energy (WtE) development, there remains a lack of studies that comprehensively analyze how waste reduction and renewable energy generation are interconnected within the WtE system. Empirical evidence shows that antecedent variables influencing waste reduction and energy production include public awareness, waste segregation at the source, government incentives like tipping fees and subsidies, the adoption of advanced technologies such as plasma or gasification, financial viability for private sector investment, and community acceptance. Without addressing these systemic factors holistically, WtE projects risk failing to achieve their dual objectives of waste reduction and energy generation. A comprehensive analysis that integrates these variables is essential to develop effective policies and ensure the long-term sustainability of WtE projects, particularly in the Indonesian context (Zhao et al., 2016).

The PLTSa Benowo has been operational since 2015, initially using sanitary landfill technology and upgraded to gasification in 2021. It processes 1,000 tons of waste per day and generates up to 12 megawatts of energy, most of which is sold to PT PLN (Kominfo.jatimprov.go.id, 2023). This study addresses the “investment strategy and operational optimization" by analyzing the financial feasibility of PLTSa Benowo using Cost-Benefit Analysis (CBA) with BCR and ROI as key indicators, complemented by sensitivity analysis on operational costs and tipping fee scenarios, while System Thinking through Causal Loop Diagram (CLD) maps dynamic interactions among waste quality, capacity, policy support, and community participation, providing strategic recommendations for improving waste sorting at source, enhancing policy support, adopting plasma technology, and diversifying revenue streams (Aulia, 2023; Qodriyatun, 2021).

LITERATURE REVIEW

Waste Management

Waste management refers to the processes of collecting, transporting, treating, and disposing of waste, alongside monitoring and regulating all related activities (Kaza et al., 2018). The grand theory underlying waste management is the Sustainable Development Theory, which emphasizes balancing environmental protection, economic growth, and social equity to meet current needs without compromising future generations (Zhang et al., 2021). Within this framework, waste is seen not merely as an environmental burden but as a potential resource that can be reintegrated into the economy through circular economy principles such as the 3Rs (reduce, reuse, recycle) and Waste-to-Energy (WtE) technologies (Abubakar et al., 2022; Kumar & Samadder, 2017).

The primary goal of waste management systems is to recover materials and energy while minimizing residual waste and reducing environmental and public health risks, particularly in developing countries where poorly managed landfills exacerbate pollution and climate change impacts (Shoddo, 2024; Shi et al., 2016). Advanced methods like composting, recycling, and WtE systems are increasingly promoted as part of sustainable waste management solutions that reduce landfill dependency, cut greenhouse gas emissions, and support long-term economic and environmental goals (Kalyani & Pandey, 2014). By applying the Sustainable Development Theory as the conceptual foundation, this study evaluates waste management not only from a technical and financial perspective but also as a critical component of climate change mitigation and the transition to a circular economy.

Waste-to-Energy (WtE) Systems

Waste-to-Energy (WtE) systems convert municipal solid waste (MSW) into electricity and heat, using waste as the primary fuel source and contributing to renewable energy development. Common WtE technologies include thermal conversion (incineration, gasification, pyrolysis), biological conversion (anaerobic digestion, composting), and sanitary landfilling with biogas recovery (Salah et al., 2023). Thermal conversion uses heat to process waste into energy, typically for lowmoisture waste or Refuse Derived Fuel (RDF) (Dawar et al., 2025). Techniques include incineration, which reduces waste volume by up to 90% and recovers materials like metals and fly ash (Morf et al., 2013; Prawisudha, 2022); gasification, which converts organic materials into syngas (Yap & Nixon, 2015); and pyrolysis, which produces bio-oil, syngas, and char (Bertone et al., 2024). Biological conversion, such as anaerobic digestion, breaks down organic waste in oxygen-free conditions to produce biogas and nutrient-rich byproducts (Kalyani & Pandey, 2014). Modern sanitary landfills capture biogas and manage leachate, but poorly managed sites in developing countries often lead to pollution and health risks (Kumar & Samadder, 2017). WtE systems reduce landfill dependency, generate renewable energy, and lower greenhouse gas emissions, but their success relies on technology optimization and proper waste segregation.

Feasibility Analysis

Feasibility analysis evaluates whether a project can meet its objectives within resource constraints (Oprea, 2010). It involves comparing projected costs with expected revenues to assess profitability and considers multiple alternatives to determine the best approach. A project is feasible when it demonstrates a reasonable chance of success, supported by sufficient resources and acceptable risks. Feasibility analysis provides a decision-making framework that aligns technical, financial, and contextual factors to ensure practical implementation (Langit et al., 2024).

Macroeconomic Impacts of Waste-to-Energy (WtE) Systems

WtE systems contribute to macroeconomic stability by addressing waste management, reducing carbon emissions, and enhancing renewable energy capacity. They diversify energy sources, reduce fossil fuel dependence, lower energy import costs, and strengthen trade balances (Krzyżostan et al., 2024). WtE projects create jobs across construction, operations, and maintenance, boosting local incomes and regional economies (Langit et al., 2024). They also stimulate growth in the energy sector and related industries, increasing GDP, especially when supported by public-private partnerships (Samreen et al., 2024). Environmentally, WtE systems reduce greenhouse gas emissions and externalities such as healthcare costs from air pollution, aligning with sustainable development goals and environmental policies (Twidell, 2021). Overall, WtE systems offer efficient waste management solutions with significant economic, environmental, and social benefits (Rahman et al., 2025).

METHODS

This study uses a mixed methods approach, which integrates qualitative and quantitative methods to provide a comprehensive analysis (Dawadi et al, 2021)). This approach was chosen to evaluate the sustainability of investment and operational optimization strategies of the Benowo Waste-to-Energy Plant (PLTSa). The qualitative method was used to explore the causal relationships between system variables using the System Thinking approach (Sarasi, 2021), while the quantitative method applied Cost-Benefit Analysis (CBA) to assess the efficiency and financial feasibility of the project (Farras et al., 2022).

The data analysis process involved several key steps. First, primary data from semi-structured interviews with internal stakeholders of PLTSa Benowo, government representatives, PLN, and academic experts were thematically analyzed to identify key variables influencing PLTSa sustainability, such as waste quality, policy support, and tipping fee revenue. Second, these variables were visualized in a Causal Loop Diagram (CLD) using Vensim software to illustrate the dynamic interconnections between factors. Third, secondary data from PLTSa financial reports, electricity capacity projections, operational costs, and tipping fee revenues (2015–2023) were analyzed using CBA to calculate the Benefit-Cost Ratio (BCR) and Return on Investment (ROI) as key indicators of financial viability. Finally, sensitivity analysis was conducted by simulating operational cost increases up to 50% and removing tipping fees to evaluate the impacts on investment feasibility and support the formulation of strategic recommendations for investment and operational optimization of PLTSa Benowo. This research is exploratory, aiming to identify the main factors affecting the sustainability of waste-to-energy systems and to develop data-driven strategies for long-term implementation.

The data for this study were collected through a combination of primary and secondary sources, in accordance with the mixed methods approach used (Wardhani & Noviaristanti, 2023). Primary data were obtained from semi-structured interviews with 7 key informants, consisting of representatives from PT Sumber Organik (PLTSa Benowo operator), the Surabaya Environmental Agency, PT PLN, the National Energy Council, and academic experts in finance, public health, waste management, and system thinking. The interviews were guided by a preliminary protocol but remained flexible to accommodate the interviewee’s responses. Secondary data, including waste processing capacity, electricity output, tipping fee and electricity sales revenue, and operational costs, were collected from official reports, academic publications, Bappenas, the Ministry of Environment and Forestry, the Surabaya Population Agency, and Kominfo Jatim. The data analyzed covered the period from 2015 to 2023, with projections up to 2032 for sensitivity analysis.

Secondary data were obtained from various sources, including waste processing capacity, electricity generation, revenue from tipping fees and electricity sales, and annual operational costs. Literature studies and academic publications were also reviewed to provide a broader context for waste-to-energy management in Indonesia (Villa et al., 2022; Farras et al., 2022). The Causal Loop Diagram (CLD) was developed to map the interactions between variables and was created using Vensim software. The CLD validation process combined Triangulation and Focus Group Discussion (FGD) to ensure the credibility and relevance of the model.

Triangulation was used to cross-validate data sources by comparing information from multiple informants, times, and places, ensuring consistency and accuracy across perspectives (Dawadi et al., 2021). However, major stakeholders were involved in FGD, which validated the CLD. To make sure they represent actual circumstances and useful insights, PLTSa Benowo management, legislators, and academic specialists closely examine the feedback loops and relationships in the diagram. Thus, Triangulation ensures data accuracy, while FGD confirms the systemic dynamics and interconnections visualized in the CLD.

On the quantitative side, Cost-Benefit Analysis (CBA) was applied to evaluate project efficiency based on data such as electricity generation, revenue from electricity and tipping fees, and operational costs. The analysis compared theoretical design capacity (maximum potential) with actual operational capacity to identify optimization opportunities. The CBA calculation includes two key parameters:

- Benefit-Cost Ratio (BCR): This metric compares the Present Value (PV) of benefits to the PV of costs.
- Return on Investment (ROI): This measures the profitability of the project relative to its costs.

These calculations help determine the project's financial viability and support strategic recommendations for investment and operational improvements.

Benefit-Cost Ratio (BCR): This method compares the value of benefits to project costs with the formula

$$\text{BCR} = \frac{\text{PV Total Benefit}}{\text{PV Total Cost}} \quad (1)$$

A project is considered feasible if the BCR ≥ 1 (Pannell et al., 2024).

Return on Investment (ROI): ROI is used to measure the return on investment against the cost of a project with the formula

$$ROI = \frac{Total\ Income - Total\ Cost}{Total\ Cost} \quad (2)$$

An ROI of > 0% indicates a positive financial gain, while an ROI of < 0% indicates a loss (Preuss, 2016).

RESULT AND DISCUSSION

Casual Loop Diagram Modeling

The CLD model consists of two diagrams, as shown in Figure 2, which describe the complex interconnections among variables in the Benowo PLTSa business scheme. The business dynamics of PLTSa are driven by revenue streams from electricity production and tipping fees. Increased waste processing capacity boosts electricity output, which is sold to PLN, generating revenue for operations and facility development. The system's sustainability depends on government support, such as budget allocations and regulatory frameworks that facilitate infrastructure growth and attract private sector investment to expand waste management capacity. However, the system faces constraints from government subsidies: while subsidies can help cover revenue gaps, excessive reliance on them risks overburdening the state budget and undermining the program's long-term viability.

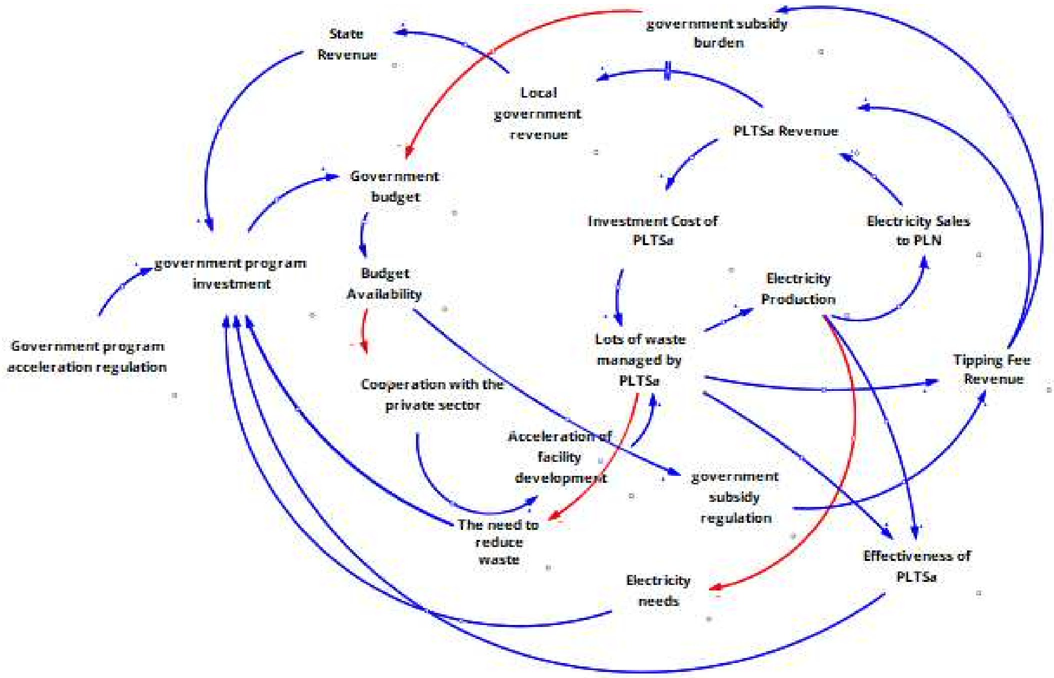

Figure 2
Casual Loop Diagram from Benowo's PLTSa Business scheme

Figure 3 illustrates how several interrelated factors contribute to the inefficiency of waste management at PLTSa Benowo. The operational dynamics begin with waste volume from Surabaya, processed at TPA Benowo to generate energy. However, the facility's capacity acts as a physical limit—when waste exceeds capacity, unprocessed waste accumulates, leading to environmental impacts such as greenhouse gas emissions (Hermansyah et al., 2024). Inefficiencies arise from inconsistent waste quality due to poor segregation at the source, limited public participation, and technological constraints that reduce processing capacity and energy conversion efficiency (Vinti et al., 2021; Azis et al., 2021).

Government support, including regulations, incentives, and subsidies, is critical for sustaining operations, but insufficient and inconsistent support further hinders optimization efforts (Farras et al., 2022). Additionally, the system's heavy reliance on subsidies, while useful for covering revenue gaps, poses long-term sustainability risks by potentially burdening the state budget. High-quality waste facilitates processing efficiency, enabling higher electricity generation sold to PLN as a key revenue source. Collaboration with the private sector can enhance infrastructure and capacity, but inefficient waste management creates feedback loops that threaten system sustainability. The success of PLTSa Benowo as a waste-to-energy management model in Indonesia depends on the holistic management of several important factors, such as waste quality, technology, public involvement, and government assistance (Prawisudha, 2022; Qodriyatun, 2021).

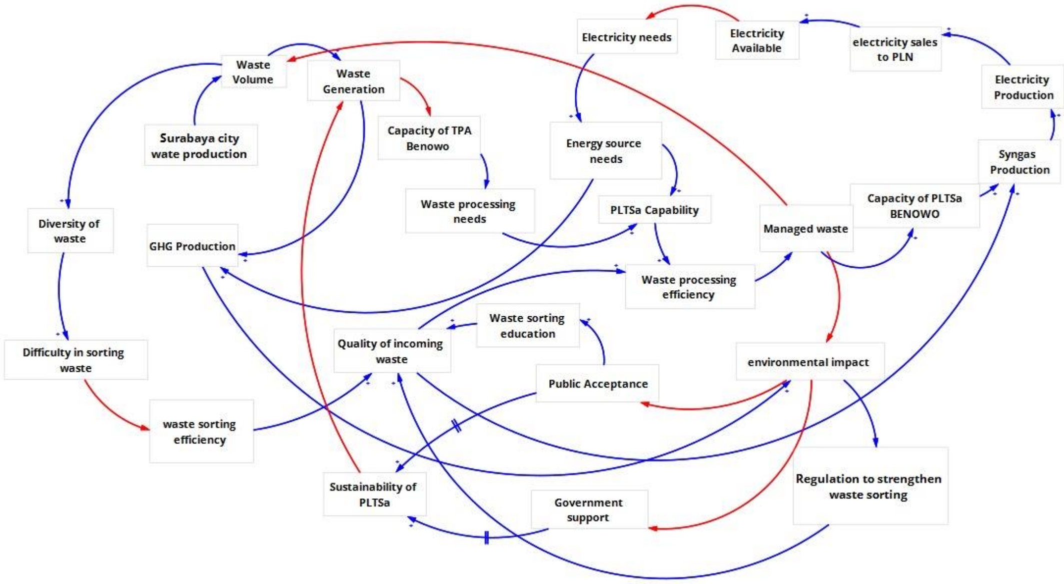

Figure 3
Casual Loop Diagram Operational PLTSa Benowo

Cost Benefit Analysis

To provide a foundational understanding for the cost-benefit analysis, Table 1 presents the projected data of the Benowo Waste-to-Energy Plant (PLTSa Benowo) based on its design capacity. The data includes estimated waste input capacity, power generation potential, operational costs, and projected revenues. This projection serves as a basis for evaluating the feasibility and economic viability of the project.

Table 1
Projected data of PLTsa benowo based on design capacity

Year	Electrical Results (MW/Year)	Electricity Sales Revenue (IDR)	Amount of Waste** (Ton/Year)	Revenue from tipping fee/year (IDR)	Operational Costs/Year (IDR)
2015	14629	30,583,533,690.00	539343.00	91,688,310,000.00	23,000,000,000.00
2016	14629	30,583,533,690.00	547500.00	93,075,000,000.00	23,000,000,000.00
2017	14629	30,583,533,690.00	567660.28	96,502,247,600.00	23,000,000,000.00
2018	14629	30,583,533,690.00	567660.28	96,502,247,600.00	23,000,000,000.00
2019	14629	30,583,533,690.00	616489.00	104,803,130,000.00	23,000,000,000.00
2020	14629	30,583,533,690.00	584000.00	99,280,000,000.00	23,000,000,000.00
2021	78840	164,823,692,400.00	578618.99	115,723,798,000.00	64,000,000,000.00*
2022	78840	164,823,692,400.00	567660.28	113,532,056,000.00	64,000,000,000.00

Year	Electrical Results (MW/Year)	Electricity Sales Revenue (IDR)	Amount of Waste** (Ton/Year)	Revenue from tipping fee/year (IDR)	Operational Costs/Year (IDR)
2023	78840	164,823,692,400.00	570778.29	114,155,658,000.00	64,000,000,000.00
2024	78840	164,823,692,400.00	575252.2838	115,050,456,760.58	64,000,000,000.00
2025	78840	164,823,692,400.00	579531.8638	115,906,372,752.40	64,000,000,000.00
2026	78840	164,823,692,400.00	583647.6867	116,729,537,342.54	64,000,000,000.00
2027	78840	164,823,692,400.00	587620.3175	117,524,063,497.71	64,000,000,000.00
2028	78840	164,823,692,400.00	591449.9465	118,289,989,300.94	64,000,000,000.00
2029	78840	164,823,692,400.00	595151.6166	119,030,323,311.22	64,000,000,000.00
2030	78840	164,823,692,400.00	598727.9935	119,745,598,690.91	64,000,000,000.00
2031	78840	164,823,692,400.00	602168.7948	120,433,758,956.64	64,000,000,000.00
2032	78840	164,823,692,400.00	605456.6928	121,091,338,553.12	64,000,000,000.00
TOTAL	**1033854**	**2,161,385,510,940.00**	**10459352.15**	**1,989,190,852,749.10**	**906,000,000,000.00**

Notes: *This value comes from a report published by Bappenas (Prawisudha, 2022), **projection data is adjusted to the population growth of Surabaya(Dinas Kependudukan dan Pencatatan Sipil Pemerintah Kota Surabaya, 2022)

While Table 1 provides projections based on the design capacity, Table 2 presents the projected data of PLTSa Benowo based on the actual capacity currently observed in operations. This comparison helps illustrate the performance gap between the ideal scenario and the real conditions, highlighting potential challenges and areas for improvement.

Table 2
Projected data of PLTsa benowo based on Actual capacity

Year	Electrical Results (MW/Year)	Electricity Sales Revenue (IDR)	Amount of Waste (Ton/Year)	Revenue from tipping fee/year (IDR)	Operational Costs/Year (IDR)
2015	5500	11,498,355,000.00	539343.00	91,688,310,000.00	23,000,000,000.00
2016	5500	11,498,355,000.00	547500.00	93,075,000,000.00	23,000,000,000.00
2017	5500	11,498,355,000.00	567660.28	96,502,247,600.00	23,000,000,000.00
2018	5500	11,498,355,000.00	567660.28	96,502,247,600.00	23,000,000,000.00
2019	5500	11,498,355,000.00	616489.00	104,803,130,000.00	23,000,000,000.00
2020	5500	11,498,355,000.00	584000.00	99,280,000,000.00	23,000,000,000.00
2021	35000*	74,216,655,000.00	578618.99	115,723,798,000.00	64,000,000,000.00
2022	35000	74,216,655,000.00	567660.28	113,532,056,000.00	64,000,000,000.00
2023	35000	74,216,655,000.00	570778.29	114,155,658,000.00	64,000,000,000.00
2024	35000	74,216,655,000.00	575252.2838	115,050,456,760.58	64,000,000,000.00
2025	35000	74,216,655,000.00	579531.8638	115,906,372,752.40	64,000,000,000.00
2026	35000	74,216,655,000.00	583647.6867	116,729,537,342.54	64,000,000,000.00
2027	35000	74,216,655,000.00	587620.3175	117,524,063,497.71	64,000,000,000.00
2028	35000	74,216,655,000.00	591449.9465	118,289,989,300.94	64,000,000,000.00
2029	35000	74,216,655,000.00	595151.6166	119,030,323,311.22	64,000,000,000.00
2030	35000	74,216,655,000.00	598727.9935	119,745,598,690.91	64,000,000,000.00
2031	35000	74,216,655,000.00	602168.7948	120,433,758,956.64	64,000,000,000.00
2032	35000	74,216,655,000.00	605456.6928	121,091,338,553.12	64,000,000,000.00
TOTAL	**459000**	**959,589,990,00.00**	**10459352.15**	**1,989,190,852,749.10**	**906,000,000,000.00**

Note: *Electricity results based on their realization (Kominfo.jatimprov.go.id, 2023)

The comparison between the design capacity and effective capacity of the Waste-to-Energy Power Plant (PLTSa) project highlights significant discrepancies that indicate the presence of technical constraints and operational inefficiencies limiting the plant's potential performance. The design capacity represents the theoretical maximum output under ideal conditions, while the effective capacity reflects the actual performance in the field (Farras et al., 2022). The data show that the design capacity is projected to generate a total of 1,033,854 MWh of electricity over the project's lifetime, whereas the effective capacity only reaches 459,000 MWh—approximately 44% of the design capacity. This gap suggests that the facility is not operating at its optimal level, likely due to inconsistent waste quality, inadequate waste segregation, technological limitations, maintenance issues, and suboptimal operational processes (Azis et al., 2021).

This underperformance directly impacts the project's revenue. Under design capacity, the total revenue is estimated at IDR 4,150.58 billion, while effective capacity produces only IDR 2,948.78 billion (about 71% of the expected value). The average annual revenue also declines by 28.9 %, from IDR 230.58 billion under design capacity to IDR 163.82 billion under effective capacity. The gap is even more pronounced in profitability: the total profit under design capacity is IDR 2,540.17 billion, compared to only IDR 1,338.38 billion under effective capacity (a 47.3% decrease). Average annual profit also drops sharply from IDR 141.12 billion to IDR 74.35 billion.

These findings underscore the critical importance of improving operational efficiency, optimizing waste management practices, and enhancing technological capacity to ensure the financial sustainability of PLTSa projects. Without addressing these systemic challenges, the potential benefits of waste-to-energy systems, such as PLTSa Benowo, cannot be fully realized (Liu et al., 2025).

Benefit-Cost Ratio

The Benefit-Cost Ratio (BCR) analysis shows that the PLTSa Benowo project is economically feasible, with a BCR of 2.58 at design capacity and 1.83 at effective capacity**.** A BCR greater than 1 indicates that the project's economic benefits exceed its costs. The lower BCR at effective capacity highlights reduced operational efficiency and underscores the need for process optimization.

Return On Investment

The Return on Investment (ROI) analysis also supports the financial viability of PLTSa Benowo. ROI at design capacity is 157.7%, meaning each IDR 1 invested yields a return of IDR 1.57, while at effective capacity, ROI drops to 83.1%, equivalent to a return of IDR 0.83. This decline emphasizes the importance of improving operational efficiency to maximize project profitability.

Sensitivity Analysis in Case of Increased Operational Costs

To better understand the impact of potential cost fluctuations on project feasibility, a sensitivity analysis was conducted by simulating different scenarios of increased operational costs. The following chart compares the Benefit-Cost Ratio (BCR) under four conditions: baseline (no increase), 10%, 30%, and 50% increases in operating costs.

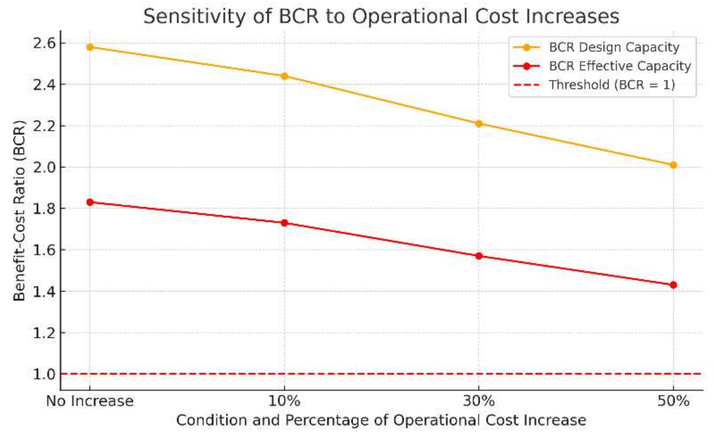

Figure 4
Comparison chart of BCR with 4 conditions, namely, without an increase in operating costs, up 10%, 30%, and 50%

The sensitivity analysis of the Benefit-Cost Ratio (BCR) in Figure 4 illustrates an inverse relationship between BCR and operational costs. At baseline, the BCR is 2.58 for design capacity and 1.83 for effective capacity, indicating strong financial viability. However, a 10% increase in operational costs reduces the BCR to 2.44 for design capacity and 1.73 for effective capacity, while a 30% increase lowers it further to 2.21 and 1.57, respectively. At a 50% increase, the BCR declines significantly to 2.01 for design capacity and 1.43 for effective capacity. Although the BCR remains above 1, indicating financial feasibility, the narrowing benefit margins reflect increasing vulnerability and reduced economic resilience.

This analysis highlights the critical intersection between rising operational costs and declining BCR, underscoring that financial feasibility becomes increasingly fragile as costs rise. Therefore, controlling operational costs is essential to maintain the economic viability of PLTSa projects.

Furthermore, these findings link directly to the Causal Loop Diagram (CLD) results. The CLD shows how factors such as waste quality, waste segregation, public participation, and processing efficiency impact electricity generation and revenue streams in the BCA. Poor waste quality and inadequate segregation increase operational costs, reduce processing efficiency, and lower BCR values, while improved management practices strengthen financial outcomes. This integration of CLD and BCA emphasizes that optimizing waste-to-energy systems like PLTSa Benowo requires not only financial calculations but also systemic interventions across waste management practices, policy support, and stakeholder collaboration (Chen & Wu, 2025).

Impact of Removing Tipping Fee Revenue

The analysis shows that the removal of tipping fee revenue significantly reduces the financial feasibility of the PLTSa Benowo project, particularly at effective capacity. Without tipping fees, the Benefit-Cost Ratio (BCR) for design capacity drops to 1.34, still indicating feasibility (BCR > 1), but for effective capacity, the BCR falls to 0.60, making the project financially unviable as costs exceed benefits (Farras et al., 2022). Similarly, the Return on Investment (ROI) for design capacity decreases to 34.21%, while for effective capacity, ROI becomes negative at -40.41%, indicating substantial financial losses without tipping fee income. These findings highlight the critical role of tipping fee revenue in maintaining the financial sustainability of waste-to-energy projects like PLTSa Benowo (Soni et al., 2025).

CONCLUSIONS, LIMITATION AND SUGGESTION

This study concludes that the sustainability of PLTSa Benowo is influenced by key factors such as waste quality, technological efficiency, regulatory support, and community acceptance. The integration of System Thinking through Causal Loop Diagram (CLD) and Cost-Benefit Analysis (CBA) provides a holistic framework to analyze these dynamics. The financial analysis confirms that the project is feasible, with a BCR of 1.83 and an ROI of 83.1% at effective capacity. Sensitivity analysis shows that increases in operational costs (by 10%, 30%, and 50%) reduce the BCR at design capacity to 2.44, 2.22, and 2.01, and at effective capacity to 1.73, 1.57, and 1.43, respectively. Excluding tipping fee revenue causes the BCR to drop significantly to 1.34 at design capacity and 0.60 at effective capacity, while ROI decreases to 34.21% and turns negative at -40.41%.

The theoretical contribution of this study lies in its integration of System Thinking and CBA, offering a novel approach for analyzing the sustainability of Waste-to-Energy (WtE) projects in Indonesia. This combined framework captures the interaction between key variables such as waste quality, operational costs, policy support, and public acceptance, while highlighting the importance of sensitivity scenarios in shaping investment strategies and operational optimization.

According to the study's practical consequences, financial survival depends on having a steady revenue stream, especially from tipping fees. Other recommended strategies include optimizing waste sorting at the source, adopting advanced WtE technologies (e.g., plasma or gasification), improving operational efficiency, and strengthening regulatory and policy support through subsidies, tax incentives, and investment frameworks. Engaging the community through education campaigns and participatory programs is also critical for improving waste quality, reducing operational costs, and sustaining long-term system performance.

This study is limited by its reliance on secondary data sources, such as reports from PT Sumber Organik, Bappenas, KLHK, the Surabaya Population Agency, and Kominfo Jatim, covering the period 2015–2023. Projections up to 2032 are based on estimates and assumptions that may not fully reflect actual conditions. Future research should incorporate more recent and validated primary data to enhance precision and explore the use of system dynamics modeling for a more comprehensive understanding of variable interrelationships in WtE projects.

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