Techno-Economic Assessment of a 1,200 Liter Rotary KilnBatch Reactor for the Production of Oil from Plastic Waste

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Techno-Economic Assessment of a 1,200 Liter Rotary Kiln Batch Reactor for the Production of Oil from Plastic Waste

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Abstract: Converting plastic waste into plastic oil is a promising solution to reduce municipal waste and create alternative fuels in developing countries.. The construction of a medium-scale plastic oil factory holds potential as a solution. Unfortunately, this idea is rarely implemented due to the lack of studies assessing its economic feasibility. This study explores two scenarios that could make this business feasible. The investment costs in this study are based on bill of quantity of the detail design of a 1,200 L capacity rotary kiln batch reactor. The evaluation methodology employed in this study involves comparing the payback period, Internal Rate of Return (IRR), and Net Present Value (NPV) of two ownership scenarios: one with the local government as the owner and the other with private companies as the owners. The optimal scenario is for the local government to own the plastic oil plant, utilizing land that is already available for the plant site. This arrangement would ensure a steady supply of plastic waste since the local government can regulate household waste segregation. The plastic oil plant in this analysis utilizes combustible non-plastic waste as the heat source for oil conversion. With an investment of 88,000 USD, the cash flow analysis shows a payback period of 1.95 years, NPV of 380,000 USD, and IRR of 57.5%. Thus, this business model is considered stable against external conditions. A sensitivity analysis shows that even with a 20% increase in plastic waste price, labor costs, and investment costs, and a 20% decrease in plastic oil price, the payback period remains attractive at 3.94 years. In order to effectively reduce plastic waste, plastic oil plants must be established everywhere. Therefore, the study also discusses a plan for ensuring the smooth expansion of plastic oil plant construction.

Keywords: waste management; alternative fuel; plastic waste; pyrolysis; new energy

1. Introduction

Municipal solid waste poses a significant problem in major cities throughout Indonesia[1,2] and many other parts of the world[3,4,5]. Studies indicate that plastic waste contributes to approximately 17.2% of the total 29 million tons of municipal solid waste[6]. Another study estimates that plastic waste generated in large cities in Indonesia accounts for 5.57%-22.63% of total waste by weight[7]. However, only 39% of the total plastic waste is collected by the formal and informal sectors, while the remaining 61% is still disposed of or burned in landfills[8]. The disposal of plastic waste in this manner has significant negative impacts on the environment. Furthermore, a Life Cycle Analysis (LCA) conducted on Indonesian waste management predicts that despite constructing a waste to energy plant and recycling plant, CO2 emissions will still amount to 4.4 million tons annually by 2030[8].

On the other hand, plastic waste has the potential to be converted into plastic oil, which can serve as a new source of energy. Given its origin as a hydrocarbon, plastic waste can be converted into fuel through pyrolysis, with a conversion rate ranging from 70-80%[9,10,11]. When it comes to municipal solid waste, plastic waste can be mixed with wood and leaves and undergo co-pyrolysis to produce fuel, although the quality will be lower than that of plastic oil derived from pure plastic[12,13]. This plastic oil contains a mixture of gasoline, kerosene, and diesel oil, which can be further fractionated to produce fuel suitable for automotive use[14]. Constructing plastic waste plants in major cities can reduce waste volume while also contributing to a decrease in fuel imports.

Numerous researchers have undertaken techno-economic studies in this field. For instance, Larrain et al. delved into the economic implications of pyrolyzing mixed plastic waste, suggesting that a plant with a capacity of 120 kt/year should operate at a minimum of 80% capacity for open-loop recycling[15]. Similarly, Fivga et al. conducted a comparable investigation, utilizing the Aspen Process Economic Analyzer (APEA) software to estimate capital investments and operational expenses for the pyrolysis plant. Their findings imply the viability of a plant with a capacity exceeding 1000 kg/h[16]. In a separate study, Lubongo et al. assessed the conversion of plastic waste into fuel within the context of the US market. According to their analysis, plants with a minimum capacity of 60 tons per day would only be economically feasible if plastic waste could be sourced at no cost[17]. Faisal et al. indicated that for a smaller capacity plant, let's say 15,000 million liters/year, the breakeven point could extend up to 25 years. Among the existing studies, none definitively affirm the feasibility of a medium-scale plastic oil plant[18]. A common thread in all these studies is the reliance on simulation-based investment cost calculations.

Constructing a plastic oil plant is a potential solution to address the plastic waste problem; however, it is crucial to take into account the costs associated with collecting and processing the waste. As such, it is logical to position plastic oil plants in close proximity to the sources of plastic waste. The plant should be equipped to process between 1-2 tons of plastic waste per day, which is equivalent to the amount produced by 2-3 villages in densely populated areas or 3-5 villages in less densely populated areas. This facility has the potential to serve between 20,000 to 40,000 individuals. The waste-to-plastic oil facility is expected to spur local economic growth and foster the creation of a circular economy in villages.

The proposal suggests using plastic oil as an ignition source for coal-fired power plants, which have traditionally relied on diesel oil. Fig. 1 shows a possible supply chain scheme for this change. Following annual maintenance, the power plant must be preheated to ensure that the boiler combustion chamber reaches the coal's flash point. Plastic oil, an alternative fuel, has the potential to replace fossil fuel-derived diesel oil. This substitution could result in a competitive price that remains unaffected by global oil price fluctuations.

On the one hand, a coal-fired power plant can help solve the waste problem in its surrounding community. This makes it a beneficial partner for plastic oil plants, as it provides market security for plastic oil production. Additionally, the value and specifications of plastic oil make it a suitable substitute for diesel oil, as its calorific value is the most important factor[19]. By selling unrefined plastic oil to the power plant, medium-scale plants no longer need to worry about the challenges of refining their plastic oil into diesel, gasoline, and kerosene. This paper presents a study that assesses plastic oil factories as a means of reducing the waste problem on Java Island in Indonesia, using it as a case study location. Java Island is an ideal case study location because it has a population of 151.6 million people who generate a large amount of plastic waste, and it is surrounded by a Coal Fired Power Plant with a total installed capacity of 24.2 GW[20,21].

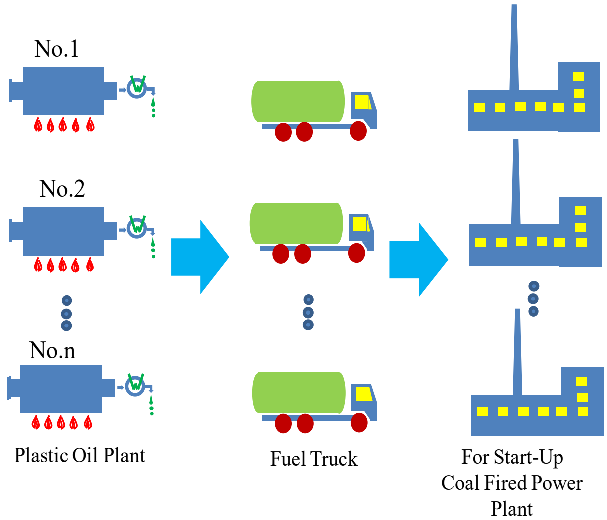


Fig 1: Proposed scheme for Plastic Oil Collection and transportation

This paper employs a specific approach aimed at minimizing both investment and operating costs:

a. The plastic oil factory used in this research has a 1,200L reactor capacity and was not available on the market, which means we could not obtain a price quotation from equipment vendors. Therefore, we calculated the investment cost for this plant capacity as the sum of the cost of purchasing materials, fabrication equipment costs, and a 20% profit margin based on our own design of the plastic oil plant.

b. The energy required to heat the pyrolysis reactor is obtained from combustible non-plastic waste. Typically, gas and oil generated during the pyrolysis process are used for this purpose[9]. However, this practice is not very advantageous because plastic oil can be sold at a higher price than using it as fuel. According to our previous research, plastic waste with no value constitutes only 6% of the total waste weight, while combustible non-plastic waste accounts for 14%[22]. Therefore, by utilizing this concept, waste reduction of up to 20% of the total waste weight can be achieved.

This research represents a first attempt to determine the techno-economic viability of a medium-scale plastic oil plant, a topic rarely explored in the scientific community. Several scenarios of plastic oil plant ownership will also be discussed. Utilizing combustible non-plastic waste as fuel will positively contribute to the economics of implementing this concept. Then from the best scenario of ownership, a sensitivity analysis will be studied of various external factors that affect the sustainability of this plastic oil plant. Therefore, we can better prepare ourselves to anticipate these upcoming factors before taking the vital step of building a plant. It will also discuss essential steps that must be taken by the government for ensuring the smooth expansion of the construction of a plastic oil plant. The results of this investigation are expected to encourage the formation of a medium-scale plastic oil ecosystem. Municipal waste will be reduced while also producing sustainable fuels.

2. Methodology

This study presents two scenarios for the ownership of plastic oil plants, as shown in Fig. 2. The first scenario involves private ownership of the plant, while the second scenario involves ownership by the local government. Given that the local government is not required to provide funding for the enterprise, the first option is preferable. Under the private ownership scenario, the company must purchase its own land, and the price of plastic waste is assumed to be 0.07 USD/kg[23]. Within this scenario, the local government can assist by loading 2,000 m2 of land for the location of the plastic oil plant. Alternatively, the government may provide tax incentives, as outlined in the Government of Republic Indonesia Regulation "PP no. 18/2015," which grants a 5% income tax relief on the investment value for specific business fields during the first 6 years.

This study will commence with a cash flow analysis, as depicted in Fig. 2. This analysis will assess the internal rate of return, net present value, and payback period of two scenarios based on factors such as investment value, operating costs, raw material procurement, plastic sales, plant lifespan, interest rates, and income tax. Subsequently, the financial evaluation results will be discussed. Lastly, this paper will conclude with a discussion of the strategy for implementing plastic oil plant construction and future research on plastic oil plant technology.

2.1 Assumption of the Investment Cost

The plastic oil plant of this particular size, powered by combustible non-plastic waste, is currently unavailable in the market. The investment costs in this study are based on bill of quantity of the detail design of a 1,200 L reactor capacity. To ensure a more realistic representation of investment costs, we have incorporated a 20% profit margin into the expenses associated with material procurement and fabrication A schematic of the plastic oil plant is presented in Fig. 3, and a three-dimensional drawing of the plant is provided in Fig. 4.

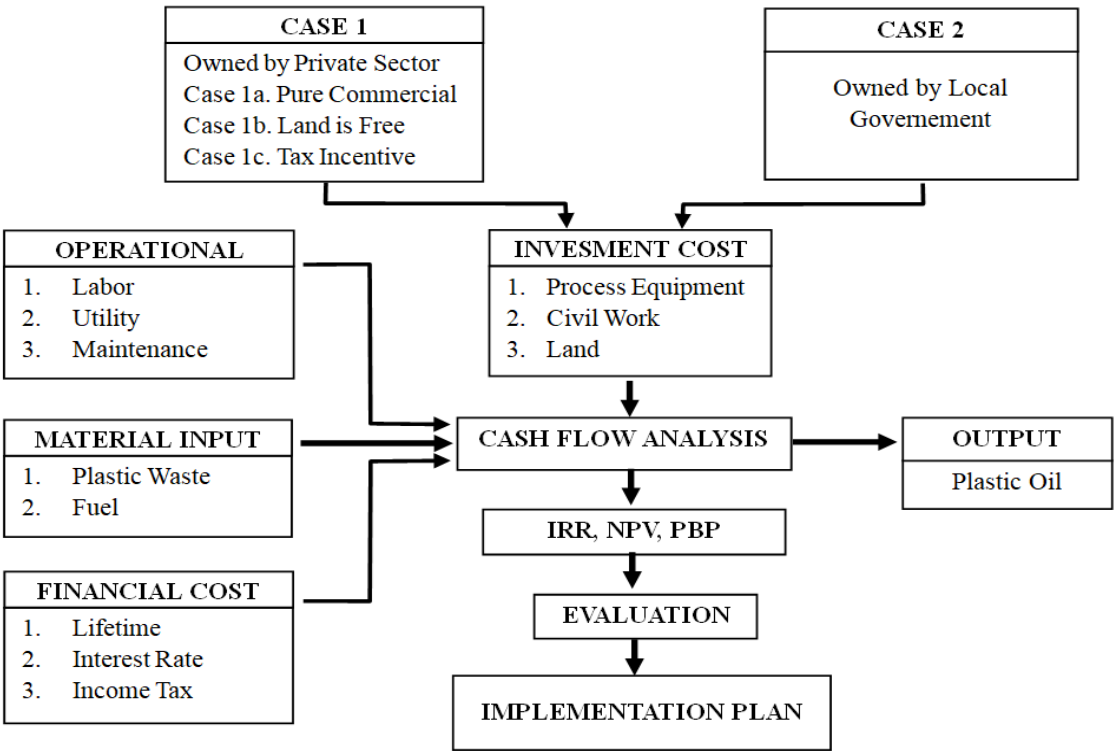


Fig. 2: Flow diagram of this study

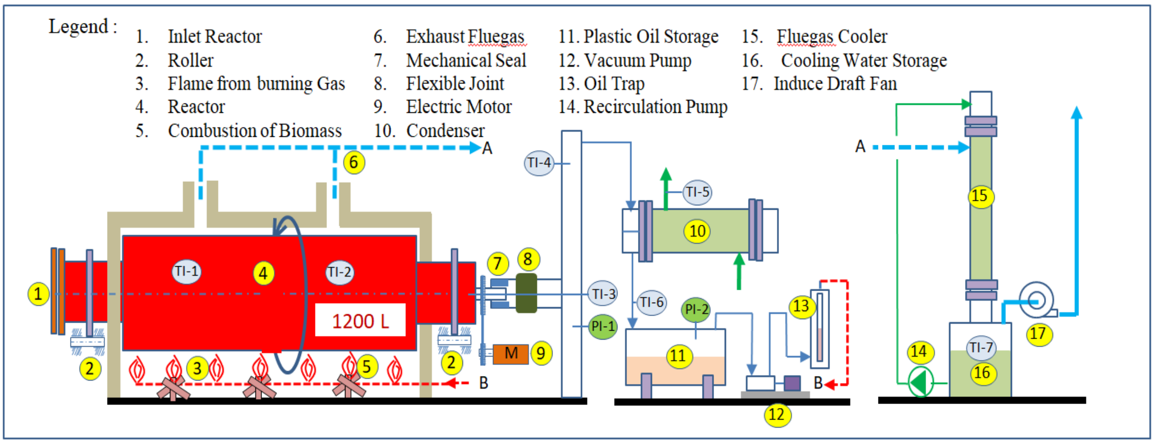


Fig. 3: Schematic of plastic oil plant capacity 1,200 L

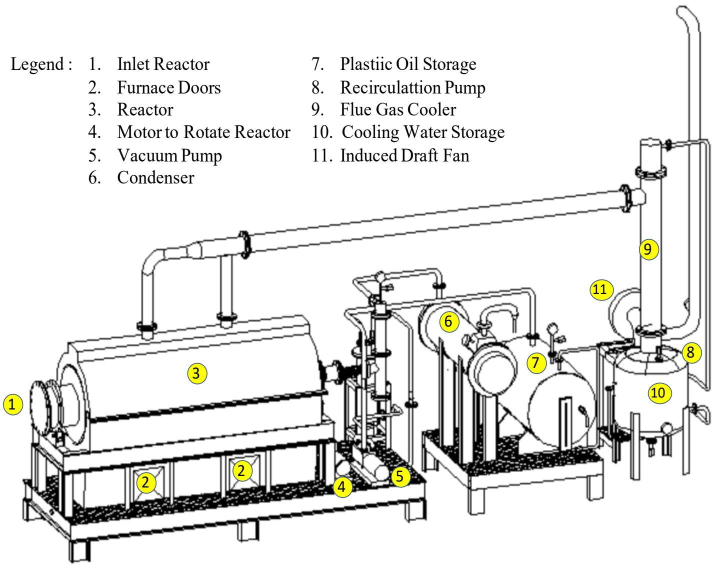
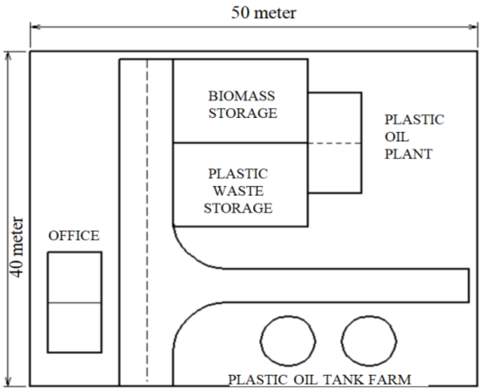


Fig.4: 3 - Dimensional Drawing of the Plastic Oil Plant

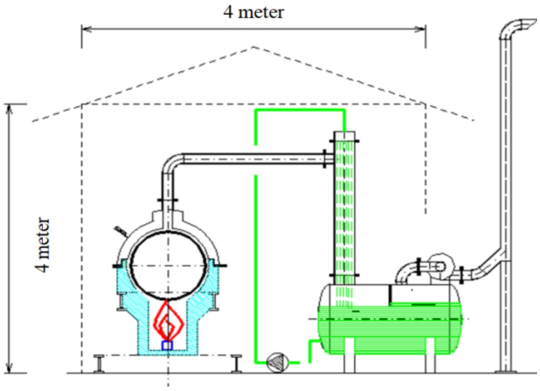
The process flow of the plastic oil plant is illustrated in Fig. 3 and is described as follows. Before beginning the process, the plastic waste is loaded through the reactor door (1) until the entire reactor is filled with plastic waste. The plastic oil plant reactor (4) is a rotating horizontal cylinder with a volume of 1,200L, heated to a temperature of 500 °C by burning non-plastic combustible waste (5) and the combustion of non-condensable gas (3) resulting from plastic pyrolysis. The reactor is supported by four rollers (2) and is driven by an electric motor (9), allowing it to rotate and ensure optimal heat transfer. As the plastic waste is heated at high temperatures in the reactor, it undergoes pyrolysis and the resulting gas flows to the condenser (10). The plastic oil condenses and is collected in the Storage Tank (11). The vacuum pump (12) maintains a slight vacuum in the reactor by extracting non-condensable gas, which is then immersed in water in the oil trap (13) to condense any remaining plastic oil. This non-condensable gas is then used as fuel in the combustion chamber. The flue gas is cooled first in the flue gas cooler (15) using recirculating cooling water. The induced draft fan (17) is responsible for drawing flue gas from the combustion chamber

Fig. 4 illustrates a 3D image of a plastic oil plant comprising three units: the reactor unit, the condensing unit, and the flue gas removal unit. The reactor features a large door in its combustion chamber, allowing for smooth entry of waste/biomass fuel. The ground floor of the reactor's combustion chamber has air holes and non-condensable gas holes. All non-condensable gases are burned, and if the reactor temperature cannot be achieved, we use waste/biomass as supplementary fuel.

According to Fig. 5, the pilot plant occupies an area of approximately 2,000 m2, with most of the space dedicated to offices, tank farms, access roads, biomass storage, and plastic waste storage. However, plastic oil factories require less than 5% of the total area. The buildings are intentionally spaced far apart to ensure safety, given that the area contains flammable materials.



(a)



(b)

Fig. 5: Plastic oil plant. **(a)** Layout **(b)** Side view

2.2 Assumption of the plastic waste.

The plastic oil factory requires plastic waste and fuel for the pyrolysis process as its material input. To collect waste, new approaches have been developed that follow the principle of segregating waste at its source. It is assumed that the local government has regulated waste segregation in its jurisdiction area. Waste is sorted into five types: (a) plastic waste, (b) combustible non-plastic waste, (c) recycled waste, (d) organic waste, and (e) waste that requires transportation to the final disposal site. Using this method, the plastic oil plant obtains clean and unmixed plastic waste, or type (a) waste. Additionally, the plant utilizes high-calorific-value waste, or type (b) waste, as fuel for its operations. Using these two types of waste as raw materials and conversion fuel reduces the amount of waste sent to final disposal sites. The cost of plastic waste collection is assumed to be 6.67 cents USD/kg for privately-owned scenarios and 2 cents USD/kg for local government-owned scenarios. Furthermore, for both scenarios the plastic oil plant receives combustible non-plastic waste at no cost.

2.3 Assumption of the plastic oil product.

The plant will produce plastic oil as its source of income. This oil is expected to sell at the same price as diesel oil, which is currently used as the start-up fuel in coal-fired power plants. Fig.s 6 and 7 present data on diesel oil prices and annual consumption from 2014-2020. On average, PT. PLN (Persero) paid 59 c USD/liter for diesel oil, with the highest price being 69 c USD/liter and the lowest price being 49 cUSD/liter. The selling price of plastic oil will need to be reduced by 11% for VAT and transportation costs, which are assumed to be 49 cUSD/liter. The annual usage of start-up oil ranges from 64 thousand KL/year to 457 thousand KL/year, with an average of 212 thousand KL/year. Thus, the potential for hundreds of plastic oil plants in the Java region is significant, even if they operate under minimum conditions

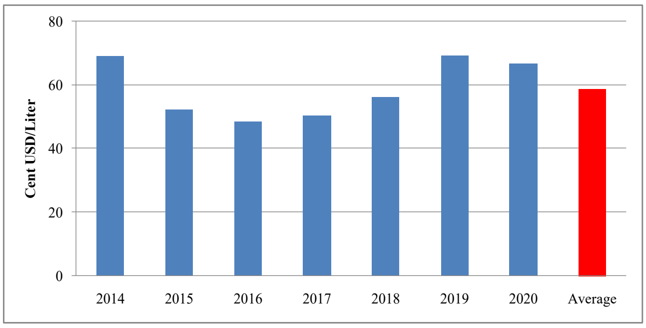


Fig. 6: The price of diesel fuel in PT. PLN (Persero) in Java

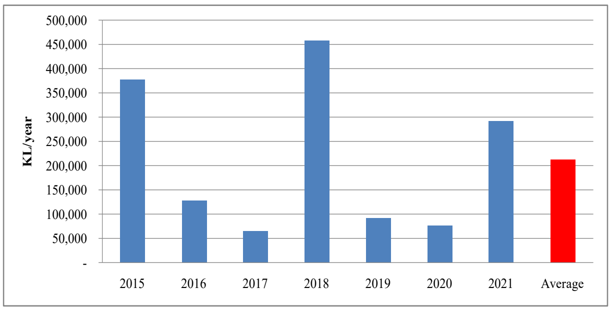


Fig. 7: Diesel fuel consumption of PT. PLN (Persero) in Java

Table 1 compares the characteristics of commercial diesel oil, which is used as fuel for start-up Coal Fired Power Plants, and plastic oil derived from various sources. Calorific value is an essential factor to consider for igniting combustion in the boiler. As shown in the table, plastic oil has a calorific value that falls within the range of commercial diesel oil. The composition of inputted plastic waste has a significant impact on the calorific value of plastic oil. Plastic waste types such as polystyrene (43 MJ/kg), polypropylene (40.8 MJ/kg), high-density polypropylene (40.5 MJ/kg), and low-density polypropylene (39.5 kg) produce a high calorific value. However, polyethylene terephthalate (28.2 MJ/kg) and polyvinyl chloride (21.1 MJ/kg) produce a low calorific

Table 1. Comparison between specification of plastic oil[19,25,26,27] vs. Pertamina B30 Biosolar[28])

Fuel Properties	Methods	Unit	Commercial Diesel Oil (Pertamina Biosolar)		Plastic Oil	
			Min.	Max.	Measurement	Reff.
Cetane Number	ASTM D613	-	48	-	66.1	[27]
Cetane Index	ASTM D4737	-	45	-	72.89	[27]
Density (at 15 °C)	ASTM D4052 / D1298	kg/m^3	2	880	747-900	[26,27,19]
Viscosity (at 40 °C)	ASTM D445	mm^2/s	-	5	1,98 - 6,36	[26,27,19]
Sulphur Content	ASTM D4294 / D5453 / D2622	%m/m	-	0.25	< 014	[25.26,27]
Distilation at 90% vol evaporation	ASTM D86	°C	-	370	270-391	[26,27]
Flash Point	ASTM D93	°C	52		15-50,5	[26,27]
Pour Point	ASTM D97 / D5949	°C	-	18	minus 67 - 15	[26,27,19]
Carbon Residue	ASTM D189 / D4530	%m/m	-	0.1	0.5	[25]
Moisture Content	ASTM D6304 / D1744	mg/kg	-	425	-	
Kandungan FAME	ASTM D7806 / D7371	% v/v	-	30	-	
Korosi bilah tembaga	ASTM D130	kelas	-	Kelas 1	Class 1	[27]
Kandungan abu	ASTM D482	%m/m	-	0.01	< 0,07901	[25,26,27,19]
Kandungan sedimen	ASTM D473	%m/m	-	0.01	0.005	[27]
Total Acid Number	ASTM D664	mh KOH/g	-	0.6	-	
Calorific Value		MJ/kg	43		39.5 - 43,0	adapted from [19] but without PVC and PET

value. Selecting the appropriate type of waste can produce plastic oil with a calorific value close to diesel oil. Another critical property to consider is viscosity, which affects the quality of burning oil in the boiler. Plastic oil has a lower viscosity than diesel oil, which is advantageous. Additionally, the lower flash point of plastic oil makes it more combustible in the boiler, providing an additional benefit

Table 2. Summary of Assumptions for Investment and Operational Cost

Description	Remarks
Investment	
Equipment	53,333 USD
Building	26,666 USD
Land, gate, fence	66,666 USD for the area of approx. 2,000 m^2 (only for private ownership scenario)
Working capital	Cost for 3 months of operation and maintenance
Conversion rate	1 USD equal 15,000 IDR
Performance	
Capacity of reactor	1,200 L/batch
Number of batches	3 batch/day
The density of plastic waste	0.26 kg/L in the reactor
The yield of plastic oil	0.65 L/kg of plastic waste
Hours of operation	16 hours/day
Days of operation	330 days/year
Number of operators	5 people for 3 batches
Maintenance cost	5% of investment in equipment and building
Electricity	10 kW
Fuel	300-400 kg of combustible non-plastic waste/batch

Furthermore, plastic oil has a lower sulphur level compared to diesel oil. The only minor drawback of plastic oil is its slightly higher ash content than diesel oil. However, since the plastic oil will be burned in the coal boiler, this higher ash content will not pose any issues. Based on this comparison of specifications, it is anticipated that the utilization of plastic oil in coal boilers will result in negligible problems.

2.4 Assumption of operational cost and financial parameters.

Another assumption in this analysis is that the operator's salary is fixed at 266.67 USD/month[29] (based on the regional average wage), and the cost of electricity is 0.11 USD/kWh[30]. Moreover, the applicable income tax rate is 25%, and equipment depreciation is calculated for 20 years. The interest rate is assumed to be 8%, and all capital costs are fully owned for investment purposes. Other assumptions for economic calculations are presented in Table 2, derived from experiments conducted in our laboratory on a smaller scale.

2.5. Economic Evaluations.

The economic performance of the plants is analyzed using various economic parameters, such as Payback Period (PP) and Net Present Value (NPV), which are calculated using the following equations.

$$\text{PP (years)} = \left(\frac{\text{Total Investment}}{\text{Net Profit}}\right) \quad (1)$$

$$\text{NPV} = \sum_{y=1}^{n} \frac{\text{NCF}_y}{(1+i)^y} \quad (2)$$

In equation (2), the variable "n" represents the plant's lifespan, while "NCF" corresponds to the net cash flow in year "y". Similarly, "i" denotes the discount rate used for the present value calculation of future cash flows. The Internal Rate of Return (IRR) is the rate of return at which the Net Present Value (NPV) becomes zero. This relationship can be expressed as follows:

$$NPV = \sum_{y=1}^{n} \frac{NCF_y}{(1+IRR)^y} - NCF_o \quad (3)$$

3. Result & Discussions

3.1 The Result of Financial Model Calculation

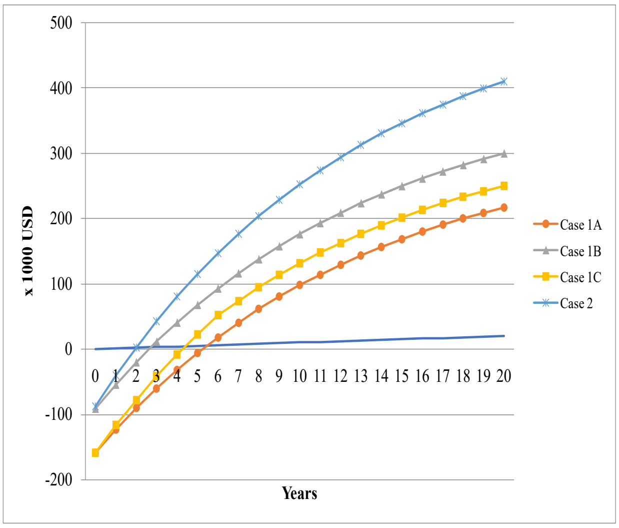


Fig. 8: Cumulative discounted cash flow (Case 1: Privately owned, 1A: Pure Commercial, 1B: Local government provides land for free, 1C: Company receives tax reduction incentives, Case 2: Local government owned

The economic calculations based on the assumptions in and data presented in, are summarized in Fig. 8. The Fig. shows the cumulative discounted cash flows (DCF) over the life of the plant for various ownership scenarios. The primary reason for the large difference in initial investment, as illustrated in Fig. 8, is the cost of land acquisition. Privately-owned plastic oil factories (Cases 1A and 1C) must first purchase land before building their plant. The initial investment also includes the cost of working capital needed to buy plastic waste during the first three months of operation. The influence of working capital is evident in the slightly higher initial investment for privately owned plastic oil (Case 1B) compared to local government ownership (Case 2).

From Fig. 8, it is apparent that all ownership scenarios experienced positive cumulative DCF growth. The case with the highest cumulative DCF growth, and therefore the most attractive option, is a plastic oil plant owned bythe local government (Case 2), followed by privately owned companies (Cases 1B, 1C, and 1A). Comparing Case 2 with Case 1B, the more expensive plastics purchased by private companies in Case 1B resulted in slower cumulative DCF growth, even though they did not need to purchase land for their plant sites. Interestingly, comparing the cases of private ownership, tax reduction accelerated cumulative growth in the first 6 years, resulting in a faster payback period.

Table 3 presents the results of calculations for various ownership scenarios, with financial feasibility indicators such as NPV, IRR, and payback period. Price of land is based from our assumption, The cost of plastic waste used in this study aligns with the prevailing selling price of plastic by collectors and waste collection communities in privately owned scenarios, which amounts to 6.67 cents USD per kilogram. In contrast, for scenarios owned by the local government, the cost of plastic waste is equivalent to the cost of collection, which is 2.00 cents USD per kilogram. The local government possesses the authority to both separate and collect plastic waste. The most attractive scenario is ownership by the local government, with a payback period of 1.95 years, IRR of 57.5%, and NPV of 379,333.33 USD. This makes investing in the plastic oil business very attractive for the local government, as they already own the land and can reduce investment costs..

Additionally, by implementing regulations on waste segregation and collection, the local government can ensure a continuous supply of plastic waste and regulate its price in the long term. The profits from the plastic oil business can also be used to support other local businesses. Multiple nearby local governments can join together to invest in this company, and are strongly advised to work collaboratively to ensure that the plant's capacity aligns with the amount of waste generated The more local governments participate in this initiative, the less money each local government has to contribute towards the investment

Table 3. Financial model calculation based on ownership

Description	Case 1 : Private Owned			Case 2
	1A. Pure Commercial	1B. Local Gov. provide land	1C. Tax Reduction Incentives	Local Government Owned
Price Of Land (USD.)	66,667	-	66,667	0
Price of Plastic Waste (cent USD/kg)	6.67	6.67	6.67	2.00
Tax Incentives	-	-	30%	
IRR	23.7%	43.5%	24.6%	57.5%
Pay Back (years)	5.27	2.65	4.97	1.95
NPV (USD)	200,377	277,933	208,224	379,140

Although the private sector is responsible for investing in the second-best scenario, the local government must still allocate government-owned land for the plant site. This scenario promises a payback period of 2.65 years, an IRR of 43.5%, and an NPV of 277,933 USD. However, another scenario that involves land acquisition as part of the investment is less attractive, as it has a payback period of over 5 years. Furthermore, the plastic oil business is still in its infancy and carries a lot of risk, including undeveloped sales structures, new technology, and other uncertainties. Therefore, even with a tax deduction, it's unlikely that this scheme will attract private sector investment

The second-best scenario offers several benefits. The local government doesn't need to allocate special funds for construction investment, and the operation is more likely to succeed if carried out by the private sector rather than managed by village administrators, who are typically trained to provide community services rather than run a company. Ultimately, having the private sector manage plastic oil plants will achieve the same end goal: reducing plastic waste and creating alternative fuels from waste in the area

Table 4. Cost of Good Sales

Description	c USD/Liter	%
Raw material	3,09	17
Labor	7,97	44
Electricity	2,98	16
Maintenance Cost	1,99	11
Depreciation	2,19	12
COGS	**18,21**	**100**

The Cost of Goods Sold (COGS) assessment is presented in Table 4, which shows the annual cost incurred to produce plastic oil divided by the amount of plastic oil produced. Based on this calculation, the COGS is significantly below the assumed selling price of 49cUSD/liter (see paragraph 2.1). Among the components of COGS, labor expenses stand out significantly. This is because, at the current scale of production capacity, a medium-sized plant employs a minimum number of people to operate successfully.. Therefore, if the plant's capacity increases, the labor component should be reduced

The labor cost is a significant factor to consider because it can significantly increase the COGS. Therefore, the medium-sized plastic oil plant may not be feasible to operate in countries with high labor costs. To make a plastic oil plant feasible in high-income countries, the only solution is to increase the plant's capacity. Additionally, the supply of raw materials is also a crucial consideration. In the future, there will be competition from other recycling technologies capable of processing plastic waste into higher-value-added materials

3.2 Sensitivity Analysis

A sensitivity analysis was conducted on the best-case scenario, where the local government owns the plastic oil plant. This analysis aims to identify significant factors that may affect the operation of plastic oil plants, enabling preventive measures to be taken if problems arise.

Fig. 9 displays the results of a sensitivity analysis conducted on several critical factors. The analysis examines the impact of changes in investment costs, loading factor reduction, conversion yield variation, fluctuations in plastic oil prices and plastic waste, and rising labor costs. These factors are tested at levels ranging from -40% to 40% of the base conditions. It should be noted that not all factors affecting production costs are included in this analysis. For instance, the cost of purchasing electricity is excluded since it is regulated by the government and is less likely to increase. Furthermore, maintenance costs are influenced only by the inflation rate.

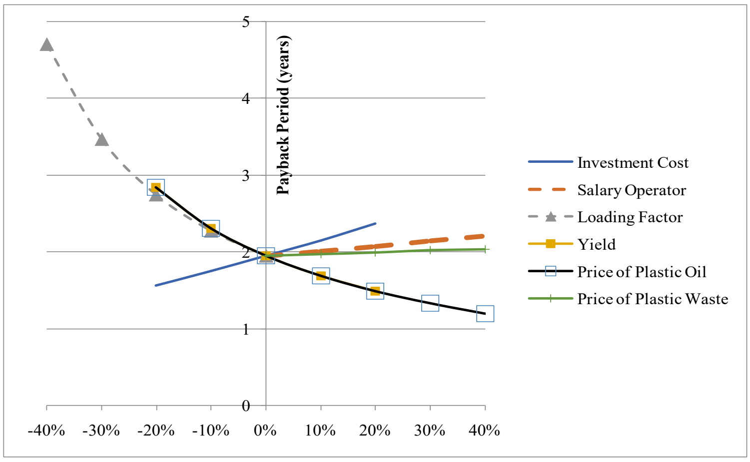


Fig. 9: Sensitivity of plastic oil plant capacity 1,200 L
(Base Case: Investment 88,000 USD, Salary 266.67 USD/month, Loading Factor: 936 kg plastic waste/day, Yield: 0.65L plastic oil/kg plastic waste, Price of plastic oil 49 cUSD/L and Price of plastic waste 2 cUSD/kg)

Labor costs are likely to increase in the future due to the expected rise in the cost of living and the obligation to comply with provincial minimum wage regulations. It is uncommon for labor costs to decrease, and this sensitivity analysis does not provide any options for doing so. Additionally, as shown in Fig. 9, a 40% increase in labor costs only resulted in a payback period increase of approximately 3 months.

The cost of plastic waste is anticipated to rise due to local government policies promoting the segregation of plastic waste. Furthermore, in the event that plastic oil becomes a widely sought-after business opportunity, the price of plastic waste may further increase due to limited availability. Thankfully, as illustrated in Figure 9, even with a 40% increase in the cost of plastic waste, the impact on the payback period remains minimal.

The investment costs are likely to rise because the equipment manufacturer necessitates a substantial amount of metal, welding wire, castable, and pumps, with many of these materials being imported. Fluctuations in material prices and a weakened Rupiah can further contribute to increased investment expenses. Nevertheless, as more plastic oil factories are constructed in the future, competition among plant manufacturers is expected to lower investment costs. As demonstrated in Figure 9, even when varying investment costs by 20%, the payback period is not significantly affected.

The yield of plastic waste conversion is a crucial factor that requires close monitoring. Oil yield reduction can occur if the plastic waste contains excessive amounts of water and dirt. A 20% decrease in yield has a more significant impact on the payback period than the same increase in investment, labor costs, or the price of plastic waste. Therefore, quality control of the plastic waste is critical to maintain the yield. As shown in Fig. 9, increasing the yield to over 0.65 liter/kg of plastic waste can accelerate the payback period. To maintain this high yield, the plastic oil plant management may implement a reward and punishment system for plastic waste suppliers.

As shown in Fig. 6, the price of diesel oil fluctuates significantly each year due to the dynamics of crude oil prices in the global market, which also affects the price of plastic oil. A 20% decrease in price results in a longer payback period, but it remains within a reasonable limit for investment. Conversely, an increase in the price of plastic oil can accelerate the payback period.

Careful consideration of the loading factor in the plastic oil plant is crucial. As depicted in Figure 9, a decrease in the loading factor of up to 40% can render the business unappealing, resulting in a payback period exceeding 4 years, which is unfavorable for small-scale enterprises. A low loading factor can stem from factors such as a shortage of plastic waste raw materials, unreliable equipment in the plastic oil plant, or an underperforming operator. However, the loading factor can still be improved by utilizing the remaining operational hours. In this calculation, there is an 8-hour safety margin as the operational hours per day are only 16 hours. These additional hours can be allocated to maintenance and other tasks to ensure the smooth functioning of the plastic oil facility and to enhance the loading factor. Given that the loading factor holds the most significant influence among the six components that affect business viability, it must be carefully anticipated from the outset.

The factors that require consideration encompass various elements that can occur simultaneously. A combination of a 20% reduction in loading and yield is highly unfavorable as it would extend the payback period to 4.3 years. Conversely, a combination of a 20% increase in labor costs, the price of plastic waste, and investment costs, along with a 20% decrease in the price of plastic oil, still results in a payback period of 3.9 years.

3.3 Implementation of Medium-Scale Plastic Oil

Significant reduction in municipal waste can be achieved through the construction of plastic oil plants in various locations. Despite several obstacles that need to be addressed, such as ensuring technological reliability, establishing a mature plastic oil market, implementing a plastic waste collection system, and providing trained human resources, the discussion on the techno-economic aspects suggests that building a plastic oil plant has great potential. Convincing the business community to invest in this endeavor remains a challenge, but the promising prospects of this innovative solution cannot be overlooked.

To facilitate the construction of a large-scale plastic oil plant, the following steps are proposed:

1) A demonstration project should be created in an area that implements waste segregation at the source into 5 types of waste, as discussed earlier. Organic waste can be used as maggot feed, while plastic and combustible non-plastic waste can be transported to other locations for processing. Sorting waste at the source is expected to become a standard practice in many areas, with a minimum of 500 houses becoming profitable.
2) A demonstration plastic oil plant should be built, utilizing waste from areas that have implemented waste segregation techniques and plastic waste from industrial areas. A recommended reactor capacity of 1,200 L or greater should be used to test the technology continuously in the long term. This will prove the reliability of the technology, allowing investors and banks to have confidence in it. The consistency of oil quality can also be studied and used as a reference for the quality standards of traded plastic oil. This plant can also be used for operator education and training in the future, ensuring an adequate supply of human resources.
3) The quality of plastic oil should be tested, and trials should be conducted on its use for start-up coal-fired power plants in collaboration with PLN. This testing is crucial to build PLN's confidence in the quality of the plastic oil, which must not put the operation of coal-fired power plants at risk in the long term.

4) Discussions should be held with the Ministry of Energy and Natural Resources, Ministry of Environment, and Local government to set plastic oil standards and regulate plastic oil plants. These institutions should issue regulations to provide a definitive legal basis for these new ventures.
5) Massive campaigns should be launched to promote this new business opportunity to the public and the banking industry. This business can reduce municipal waste and produce plastic oil, which is guaranteed to be purchased by PT PLN (Persero). With this assurance, the banking sector is more likely to grant credit for producing plastic oil, provided there is a guarantee for the volume of plastic garbage that will be processed.

3.4 Recommendations for Research and Development of Plastic Oil Plants in the Future

This techno-economic study still has limitations since the investment costs rely on the outcomes of cost calculations derived from detailed designs. The subsequent phase involves establishing a medium-scale plant that can effectively operate, enabling a comprehensive evaluation not only of the investment costs but also the operational expenses and the quality of the oil obtained from different and variable raw materials, specifically municipal plastic waste. Furthermore, the current design is founded on a batch-based system, which possesses various weaknesses that need to be addressed.

Firstly, the plant must be shut down and cooled to facilitate ash removal, which leads to reduced effective operating hours per day. Additionally, reheating the reactor upon reoperation is inefficient from both an energy and operating standpoint. Moreover, the plastic oil produced still contains many impurities due to the charcoal being carried away by the plastic oil vapor and easily entering the rotary kiln reactor outlet at the axis of the reactor. This low altitude prevents the charcoal from settling down, which further reduces the quality of the plastic oil.

To address these weaknesses, the following design improvements are proposed:

1) The plastic oil plant should be able to operate continuously with a continuous feeding system, even during ash removal. This will enable the plant to run without interruption, thus maximizing running time and energy efficiency.
2) Research should be conducted to investigate the potential for larger plant capacities to improve the plant's economy.
3) The plastic oil plant should be able to accommodate plastics with high levels of impurities, eliminating the need for pre-cleaning plastic waste.
4) The plant should be able to process various types of plastic waste, including those containing chlorine. Absorbent technology, both in-situ and ex-situ, can be used to absorb these unwanted components, preventing their release into the gas phase.
5) Non-condensable gases, which contain high percentages of hydrogen and methane, should be bottled and commercialized. Combustible non-plastic waste should be used for heating during the pyrolysis process, as it is abundant and free of charge. This will improve the plant's overall economy.

4. Conclusion

Investing in a medium-capacity plastic oil plant has the potential to be a profitable venture, with the most favorable scenario being the plant's ownership by the local government. A plastic oil plant reactor with a capacity of 1,200 L and an investment cost of $88,000 would result in a payback period of 1.95 years, a net present value (NPV) of $379,140, and an internal rate of return (IRR) of 57.5%. The second-best scenario involves private ownership, but it comes with certain conditions, such as the local government providing the private sector with a free land site for the plant.

The research has also revealed other significant findings:

- Sensitivity analysis of the best-case scenario showed that the investment remains attractive even with up to 20% increases in labor costs, investment costs, raw material prices, and selling price of plastic oil.
- However, the investment is susceptible to decreases in loading factor and yield, emphasizing the importance of ensuring the availability of high-quality plastic waste raw materials, maintaining reliable plant operations, and employing skilled operators. In conclusion, the research affirms that investing in a medium-scale plastic oil plant is indeed feasible. This investment can help reduce plastic waste volume and contribute to the production of alternative fuels.
- To encourage the widespread construction of plastic oil plants and achieve a substantial reduction in plastic waste, collaborative efforts from stakeholders such as businesses, regional governments, research institutions, and PT. PLN (Persero) are essential.

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Nomenclature

COGS	Cost of Good Sales
IDR	Indonesia Rupiah (Rp.)
IRR	Internal Rate of Return (%)
PP	Payback Period (Years)
LCA	Life Cycle Assessment

NPV	Net Present Value (USD)
PT	Perseroan Terbatas / Limited Company
USD	United Stated Dollar ($)
VAT	Value Added Tax (%)

References

1) H. Sudibyo,Y.S.Pradana, A.Budiman, W.Budhijanto," Municipal Solid Waste Management in Indonesia - A Study about Selection of Proper Solid Waste Reduction Method in D.I. Yogyakarta Province", Energy Procedia, Volume **143**, December 2017, Pages 494-499.
2) Syafrudin, M.A. Budihardjo, N.Yuliastuti, B.S.Ramadan," Assessment of Greenhouse Gases Emission from Integrated Solid Waste Management in Semarang City, Central Java " Indonesia , Evergreen, **8**(1) 23-35 (2021). https://doi.org/10.5109/4372257
3) R.Bian,J.Chen,T.Zhang, C.Gao,Y.Niu,Y.Sun, M.Zhan,F.Zhao, G.Zhang, "Influence Of The Classification Of Municipal Solid Wastes On The Reduction Of Greenhouse Gas Emissions: A Case Study Of Qingdao City, China", Journal of Cleaner Production, Volume **376**, 20 November 2022, 134275
4) A. Misganaw, B. Teffera, "An assessment of the waste-to-energy potential of municipal solid wastes in Ethiopia", Bioresource Technology Reports, Volume **19**, September 2022, 101180
5) Berisha, L.Osmanaj, "Kosovo Scenario for Mitigation of Greenhouse Gas Emissions from Municipal Waste Management", Evergreen, **8**(3) 509-516 (2021). https://doi.org/10.5109/4491636
6) Ministry of Enviroment and Forestry of the Republic of Indonesia, 2021. National Waste Management System (In Indonesian) https://sipsn.menlhk.go.id/sipsn/#parallax ,Accessed date: 12 September 2022.
7) P.Lestari, Trihadiningrum,"The impact of improper solid waste management to plastic pollution in Indonesian coast and marine environment", in Marine Pollution Bulletin,Vol.**149**, December 2019.
8) R,K.Neo, G.C.Y.Soo, D.Z.L.Tan, K.Cady, K.T.Tong and J.S.C.Low, "Life Cycle Assessment Of Plastic Waste End-Of-Life For India And Indonesia", in Resources, Conservation and Recycling, Vol. **174**, November 2021.
9) D. Lee, H. Nam, S. Wang, H. Kim, J.H. Kim,Y.Won,B.W. Hwang, Y.D. Kim,H.Nam, K.H.Lee, H.J Ryu, "Characteristics of fractionated drop-in liquid fuel of plastic wastes from a commercial pyrolysis plant", in Waste Management **126** (2021) 411–422.
10) Y.Zhang, G.Ji,D.Ma, C.Chen,Y.Wang,W.Wang, Li, "Exergy and energy analysis of pyrolysis of plastic wastes in rotary kiln with heat carrier", Process Safety and Environmental Protection **142** (2020) 203-211.
11) N.I.A.Kameel,W.M.W.Daud, M.F.A.Patah, N.W.M. Zulkifli, "Influence of reaction parameters on thermal liquefaction of plastic wastesinto oil: A review", Energy Conversion and Management: X **14**(2022) 100196.
12) D.Supramono,J.Edgar, "Characteristics of Non-Polar Bio-oil Produced by Co-pyrolysis of Corn Cobs and Polypropylene using CO2 as Carrier Gas", Evergreen, **6**(1) 78-84 (2019). https://doi.org/10.5109/2328407
13) E.Kusrini, D.Supramono,M.I.Alhamid, S.Pranata, L. D. Wilson, A.Usman, "Effect of Polypropylene Plastic Waste as Co-feeding for Production of Pyrolysis Oil from Palm Empty Fruit Bunches", Evergreen, **6**(1) 92-97 (2019). https://doi.org/10.5109/2328410
14) K. Janarthanan, P. Sivanandi, "Extraction and characterization of waste plastic pyrolysis oil for diesel engines", Journal of Cleaner Production, Volume **366**, 15 September 2022, 132924.
15) M.Larrain, S. van Passel, G. Thomassen, U. Kresovic, N. Alderweireldt , E.Moerman, P. Billen, "Economic performance of pyrolysis of mixed plastic waste: Open-loop versus closed-loop recycling", Journal of Cleaner Production, Volume 270, 10 October 2020, 122442.
16) A.Fivga, I. Dimitriou, "Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment", Energy , Volume 149, 15 April 2018, Pages 865-87
17) C.Lubongo, T.Congdon, J.McWhinnie, P. Alexandridis, "Economic feasibility of plastic waste conversion to fuel using pyrolysis", Sustainable Chemistry and Pharmacy, Volume 27, June 2022, 100683
18) Faisal,M.G.Rasul,M.I. Jahirul,D. Schaller, "Pyrolytic conversion of waste plastics to energy products: A review on yields, properties, and production costs", Science of The Total Environment Volume 861, 25 February 2023, 160721
19) S.D.A.Sharuddin, F.Abnisa, W.M.A.W.Daud, M.K. Aroua, "Pyrolysis of plastic waste for liquid fuel production as prospective energy resource", IOP Conf. Series: Materials Science and Engineering **334** (2018) 012001
20) Indonesia Central Bureau of Statistic (BPS), Populaton Census Result (in Indonesian) 2020 No. 7/01/Th. XXIV, 2021.
21) Ministry of Energy and Mineral Resources, Government of Indonesia, Statistic of Electricity 2020.
22) A.Kismanto, L.M.T.Nainggolan, "New Strategies and Innovations for Handling Municipal Waste " (In Indonesian) , LKTI Tangerang City, 2022.
23) Price of Plastic Waste per Kg at Collectors and Waste Banks (https:// harga. web.id/harga-limbah-plastik-per-kg.info , Accessed date September 12th, 2022)

24) PLN, https://web.pln.co.id/statics/uploads /2021/07/Statistik-PLN-2020.pdf, Accessed date: September 12th, 2022
25) M.Kusenberg,A. Zayoud, M. Roosen, H. D. Thi, M. S. Abbas-Abadi, A. Eschenbacher, U.Kresovic, S. De Meester,K. M. Van Geem, "A comprehensive experimental investigation of plastic waste pyrolysis oilquality and its dependence on the plastic waste composition", Fuel Processing Technology **227** (2022) 107090.
26) M. Z. H. Khan, M. Sultana, M. R. Al-Mamun, and M. R. Hasan, "Pyrolytic Waste Plastic Oil and Its Diesel Blend : Fuel Characterization", Journal of Environmental and Public Health, Volume **2016**, 7869080.
27) W.Arjharn, P.Liplap, S.Maithomklang, K.Thammakul, S. Chuepeng, E. Sukjit, "Distilled Waste Plastic Oil as Fuel for a Diesel Engine: Fuel Production, Combustion Characteristics, and Exhaust Gas Emissions", ACS Omega 2022, **7**, 9720−9729
28) Pertamina, "Product Specification of Fuels 2020" (in Indonesian).
29) Tempo, List of Latest Jabodetabek UMR 2022 from Highest to Lowest (https://bisnis. tempo.co/read/1627858/daftar-umr-jabodetabek-terbaru-2022-dari-tertinggi-hingga-terendah#:~:text=%2D%20UMR%20Tangerang%20Selatan%202022%20(UMK,Rp%204.217.206%2C00., 2022).
30) PLN, Determination of Electricity Tariff Adjustment (Tariff Adjustment) July- September 2022 (https://web.pln.co.id /statics /uploads2022/06/TA-Juli-s.d-Sept-2022-3.jpg, 2022).
31) K.Ibadurrohman, I.Gusniani, D.M. Hartono, N.Suwartha, "The Potential Analysis of Food Waste Management using Bioconversion of The Organic Waste by The Black Soldier Fly (Hermetia illucens) Larvae in The Cafeteria of The Faculty of Engineering, Universitas Indonesia", Evergreen, **7(**1) 61-66 (2020). https://doi.org/10.5109/2740946
32) Y. Kodera,T.Yamamoto,E.Ishikawa,"Energy- and economic-balance estimation of pyrolysis plant for fuel-gas production from plastic waste based on bench-scale plant operations", Fuel Communications, Volume **7**, June 2021, 100016