



Techno-economic evaluation of biofuels production from RBDPO using metal with zeolite support as strategies to end crude oil dependence

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ABSTRACT

Background: The production of sustainable aviation fuel and bio gasoline from refined bleached degummed palm oil (RBDPO) has attracted increasing attention as a strategy to support low-carbon energy development. However, due to the complexity of the liquid product composition, determining the dominant reaction pathways and evaluating the technical and economic feasibility of the process remain challenging. This study aims to evaluate the techno-economic feasibility of hydrodeoxygenation of RBDPO under atmospheric to intermediate pressure conditions. **Methods:** The process technology was developed based on mass and energy balances and financial modelling. Atom mass balance combined with error minimization was applied to identify the dominant reaction pathways. Process simulations were performed using Aspen HYSYS, while laboratory data were used as the basis for economic evaluation. Equipment costs were estimated using Aspen Capital Cost Estimator to determine the total capital investment. **Findings:** The results indicate that several reactions occur during biofuel (bioavtur and bio gasoline) production, including hydrodeoxygenation, hydro decarboxylation, cracking, and polymerization. A standalone bioavtur plant requires a capital expenditure (CAPEX) of approximately USD 87,775,899 and an operating expenditure (OPEX) of USD 6,487,559, assuming an exchange rate IDR 15,500 per USD. The financial analysis yields an Internal Rate of Return (IRR) of 12.59% and a Net Present Value (NPV) of IDR 685,679,000,000. In comparison, a bio gasoline plant requires a lower CAPEX of USD 75,256,210 and an OPEX of USD 5,944,681 under the same exchange rate. Furthermore, it demonstrates better financial performance, with an IRR of 15.46% and a NPV of IDR 346,690,000,000. **Conclusion:** The results demonstrate that hydrodeoxygenation of RBDPO is technically feasible and economically viable under atmospheric to intermediate pressure conditions. These findings provide a practical basis for developing commercially competitive bioavtur and bio gasoline production systems. **Novelty/Originality of this article:** This study combines reaction pathways analysis and techno-economic evaluation of RBDPO hydrodeoxygenation for sustainable biofuel production.

KEYWORDS: bioavtur; biogasoline; techno economic study.

1. Introduction

Based on the data, Indonesia, which has the 4th largest population in the world, was only able to produce crude oil at a rate of 887,000 barrels per day (bbl/d) in 2020 (U.S. Energy Information Administration, 2021). This production is a significant decline, as Indonesia was capable to produce crude oil up to 2.38 million bbl/d in 1961 (Kaufmann, 1962). This situation resulted in Indonesia no longer being an OPEC member since 2009.

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Naturally, Indonesia is consider seeking alternative energy sources that could substitute the energy shortage caused by the reduction in crude oil production. There are several alternatives that have been prepared by the Indonesian Government. Among of these is the effort to increase crude oil production to 1,000,000 barrels/day by the year 2030 (Office of Assistant to Deputy Cabinet Secretary for State Documents & Translation, 2020). Several fields where production will be increased are located on Sumatra Island and Java Island. On Sumatra Island, Duri and Minas are the main pillars for the rejuvenation and increasing crude oil production in several wells. On Java, there are increasing oil productions in the Cepu and Banyu Urip blocks have by the year 2021. Indonesia is also showing an increase in exploration and production activities in Kutai, West Papua, and around the Arafura Sea. Compared to 1961, the current crude oil production volume in Indonesia is insufficient. This can be seen from the fact that Indonesia imports 401,169 barrels/day of crude oil (*Kementerian Energi dan Sumber Daya Mineral/Ministry of Energy and Mineral Resources*, 2024). Other energy sources are required to substitute for crude oil-based fuels.

New and renewable energy is one of the alternatives Indonesia can use to full fill its energy shortage. Based on regulations and legislation, the National Energy General Plan (*Rencana Umum Energi Nasional*), Indonesia had set a target for new and renewable energy use to reach 23% by 2025, as stipulated in Presidential Regulation No. 22 of 2017 on the National Energy General Plan/*Rencana Umum Energi Nasional* (RUEN). However, as of 2024, the achievement of this renewable energy usage has not yet reached 20%. Consequently, the target for the renewable energy mix for 2025 has been adjusted to only 17% – 19%. Until now, the most significant use of new and renewable energy fuels has been in biofuel and electric vehicles. The planned use of biofuel, primarily B40 biodiesel, is expected to reach 15.6 million kiloliters (kl) by 2025. Throughout 2019, the average monthly import of diesel fuel dropped by 45%, and by 2020, Indonesia was no longer importing diesel fuel. As a result, Indonesia managed to save foreign exchange reserves totaling 63.4 trillion rupiahs (*Badan Pengelola Dana Perkebunan/Plantation Fund Management Agency*, 2025). Besides that, biofuel using is one of solution to overcome from greenhouse effect. one of the challenging aspects of the environment is carbon dioxide emission or we call it greenhouse gas emission. Many sources of greenhouse gas emissions cause those challenging problems. Coal power plant-based, transportation and forest fires are the most common cause of greenhouse gas emissions in many countries. Indonesia is one of the countries that have problems with greenhouse gas emissions because of those sources. Based on the data, Indonesia still uses 86% of oil as fuel for transportation and 14% as biofuels (Institute for Essential Services Reform, 2022). Moreover, increasing passengers and cargo in the air transportation industry also creates problems and adds carbon dioxide emissions to the atmosphere because the demand for jet fuel is increased (Wang et al., 2022).

Aviation is one of the industries that contribute to greenhouse gas emissions, avtur is one of them. The development of the aviation sector will immediately have an impact on the generation of greenhouse gas emissions (Nuryadin et al., 2023). Since Covid 19 started in 2020, the world has needed clean combustion technologies to keep the health of the human body and reduce greenhouse gas emissions. Biofuels, such as biodiesel and bio-jet fuel or bioavtur, are one of the energy sources that produce lower emissions than conventional sources of energy. Same with other biofuels, bioavtur and biogasoline needs sustainable raw material. These energy sources also can support the sustainability and the impact of the energy system on resources and society needs and are in line with the Sustainable Development Goals (SDGs) of the United Nations (Chong et al., 2022). This thing become important and challenging since vegetable oil in Indonesia is also edible oil. The techno-economic evaluation can become a solution to meet industrial needs and consumer prices. The current pathways to produce bioavtur from efined, bleached, and deodorized palm oil (RBDPO) are hydrodeoxygenation, and hydrodecarboxylation, well-known as hydroprocessed esters and fatty acid (HEFA or HRJ). Besides this process, there are alcohol-to-jet (ATJ), hydrothermal liquefaction (HTL), and direct sugars to hydrocarbons (DSHC).

The processes produce mostly straight chains of hydrocarbon, ranging from C7 to C16 (Mawhood et al., 2016). It also analogue to produce biogasoline.

Recent studies show that hydrodeoxygenation (HDO) is an important process for upgrading biomass into higher-quality biofuels. This process helps remove oxygen from bio-oil, which improves fuel stability and makes it more suitable for use as transportation fuel. In the last few years, many researchers have focused on improving catalyst performance, such as using NiMo, CoMo, and noble metal catalysts, to increase the yield of jet fuel-range hydrocarbons and reduce hydrogen consumption (Elliott, 2007; Kubička & Kaluža, 2010). Operating conditions, including temperature, pressure, and hydrogen flow, also play an important role in determining the efficiency of the process (Furimsky, 2000). More recent work has explored alternative ways to reduce hydrogen use, since hydrogen is one of the main cost drivers in HDO. Some studies suggest using in situ hydrogen generation or improving catalyst design to make the process more efficient and stable (Wang & Tao, 2016). These developments are important because they can lower production costs and make the process more practical for large scale applications. From an economic perspective, biofuels produced through HDO are considered promising because they can be used directly in existing engines, especially in the aviation sector. Bioavtur, for example, is seen as a key option to reduce carbon emissions from aviation. However, the economic feasibility of this process still depends on several factors, such as feedstock price, hydrogen cost, catalyst lifetime, and plant scale (Pearlson et al., 2013). In addition, recent studies highlight that process integration and energy efficiency are important to improve overall profitability.

Even though there have been many improvements, studies that combine technical analysis and economic evaluation are still limited. Therefore, further research is needed to better understand how HDO technology can be applied on a larger scale, especially for bioavtur production from palm oil-based feedstocks. In this study, the raw material price is the key factor in determining whether the plant will be profitable or not. In Indonesia, many kinds of raw material can be utilized as feed to produce bio-based fuel. One of the abundant raw materials in Indonesia is palm oil-based and Indonesia became the first producer of palm oil-based with 46 billion tons each year (Biro Humas Kementerian Perdagangan, 2024). This is a key consideration to select a raw material basis. Although Indonesia can now be considered self-sufficient in diesel fuel, the country still imports crude oil from various nations. This indicates that the nation's foreign exchange reserves are still being drained due to the use of imported crude oil. Therefore, the use of appropriate technology that can process biofuel from vegetable oil is necessary to minimize the foreign exchange spent on purchasing imported crude oil.

There are several alternatives to minimize the use of state foreign exchange. One of them is development of refineries that raw material are vegetable oil and appropriate technology application. In Indonesia, there are several catalyst plants that developed from several industry and university. At Institut Teknologi Bandung (ITB), one of university in Indonesia has technology Nickel Molybdenum catalysts with ZSM-5 support. The other technology, there is technology Cobalt-Molybdenum with H-ZSM-5 support that developed by Universitas Gadjah Mada (UGM). Nickel-Molybdenum catalyst with ZSM-5 support can direct vegetable oil become biofuel. In the other hand, cobalt-molybdenum catalyst with H-ZSM-5 support can direct vegetable oil into biofuel also. The difference lies in the produced product. Nickel-Molybdenum catalyst can direct vegetable oil into gasoline fraction and Cobalt-Molybdenum can direct vegetable oil into jet fuel fraction. The other difference lies in the operation condition. Nickel-Molybdenum catalyst should be operated in 450 °C-600 °C with 4 atm pressure, the other can be operated in 300 °-350 °C with atmospheric pressure (Asnawati et al., 2025). In this study, the writer will describe the process of converting vegetable oil into biofuel. The biofuels consist two kinds of biofuels, the first is bioavtur and the second is biogasoline. After that, the process will become basic to calculate all the needed equipment. After that, the economic aspect can be calculated using financial modelling. The economic aspect consists of the rate of interest, break-even point, net present value, and internal rate of return. All of the aspects will become the basis of evaluation to determine whether it is feasible to build or not.

2. Methods

Refined bleached degummed palm oil (RBDPO) is used as raw material for biofuel production. The raw material base is 10,000 liter/h at concentration 99.5% wt. In this section, the process of production RBDPO into biofuel is modeled in Aspen HYSYS. There are three sections in chemical processes to produce biofuel from RBDPO. The overall process consists three sectionsof three main sections: are pretreatment of raw material or raw material, main reaction process to produce biofuel from RDBPO, and purification to purify biofuels until 99.5%. The main process is consisted ofconsists of two processes. The first is used Cobalt Nickel Molybdenum catalyst with H-ZSM-5 support and the other one is Nickel Molybdenum ZSM-5 catalyst. The simulation model is developed based on laboratory-scale experimental data and is used as the basis for further economic evaluation.

2.1 Process overview

Laboratory Bioavtur Production in Laboratory Scale, the process in experiment will be analogue in the software simulation that will use to simulate the process. The Bioavtur is synthesized from raw material. Raw materials are input into feed chamber. After that, Co/Z-Mo/Z catalyst are placed in furnace with ratio 1:100 of raw materials. Then, hydrogen gas is flowed into raw materials chamber. Then furnace is heated until 450 °C and reaction is happened. This reaction is occurred in atmospheric pressure. With flow of hydrogen, raw materials carried away with it. The obtained product from reaction is cooled in condenser. In this experience, gas product is allowed away. Biogasoline Production in Laboratory Scale: The process in experiment will be analogue in the software simulation that will use to simulate the process. The Biogasoline is synthesized started with raw material. Raw materials are input into feeder. After that, furnace is heated until 500-550 °C and reaction is occurred in plug flow reactor. This reaction is occurred in 2 - 4 atm. With flow of hydrogen, raw materials carried away with it. The obtained product from reaction is cooled in condenser. In this experience, gas product is allowed away.

The simulation was performed using Aspen HYSYS, a process simulation software developed by AspenTech, to simultaneously simulate hydrodeoxygenation, hydrodecarboxylation, and cracking (AspenTech, 2025). In this simulation, there are some preparations should be provided. The first is determining components that will be used in simulation. The component is consisted raw material and product and is provided by HYSYS Databanksin simulation software. The raw material was RBDPO and was represented by triolein (C57H104O6) (Wibowo et al., 2020). The raw material is represented by triolein because it is the most abundant component in vegetable oil (Kos et al., 2007). Assuming it as the dominant component in vegetable oil to simplify the model while maintaing represesantive behavior. The second is fluid package. Fluid package is used to determined calculation in some aspects and properties. Those were calculation of physical, thermodynamic, and properties (Tao et al., 2017). The third is reaction. The reaction was calculated with the mass balance concept. Due to the complexicity of the reaction network, the reaction mechanism was approximated using lumped approach based on mass balance and experimental GC-MS results Data GC-MS that represented the area per each component was then transformed into a mass fraction (Nugraha & Nandiyanto, 2021). The Gas Chromatography–Mass Spectrometry (GC-MS) area data were converted into mass fraction and used as as constraints in determining product distribution.

There many products that was chosen in this simulation, that were n-alkene, iso-alkene, paraffin, aromatics, liquefied petroleum gas (LPG), and off gas. After this, the property method was determined in this process simulation, then Peng Robinson was employed in this simulation (Hafeez et al. 2021). The simulation is set based on Figure 1. The capacity of raw material is 10 ton/h. Several assumptions were applied in reaction modeling: Total atomic balance (C, H, and O) between reactants and product is conversed, Product distribution follows laboratory data within defined constrains, Reactions are modeled as

equilibrium reaction with fixed conversion (up to 100%), Catalyst deactivation and side reactions (e.g., coke formation) are indirectly included in product distribution.

There many products that was chosen in this simulation, that were n-alkene, iso-alkene, paraffin, aromatics, LPG, and off gas. After this, the property method was determined in this process simulation, then Peng Robinson was employed in this simulation (Hafeez et al., 2021). The simulation is set based on Figure 1. The capacity of raw material is 10 ton/h. After input the component, the mechanism of reaction could be determined using laboratory data of GCMS that were transformed into mass fraction. The result composition from GCMS will be analogue with the data of LPG composition, gasoline composition, or jet fuel composition. After that, the concept of mass balance was applied. Total C atom in the raw material will be same as the total C atom in the product. After that, minimization of error was employed to adjust the product based on data. The product composition is used as a constraint in the minimization. Table 1 shows the data laboratory that explains the composition of the product from the reaction and the range of the constraint.

Table 1. Product composition from laboratory research

Composition	Percentage	The constrain (percentage)
Liquid product	45.75%	40% - 50%
Gas Product	50.16%	45% - 55%
Coke	0.23%	0% - 5%
Residue	3.87%	0% - 5%

For example, minimization error of the liquid product. The constrain means could not exceed 50% and could not be less than 40%, then gas product could not exceed 55% and could not be less than 45%. Coke not exceed 5% and could not be less than 5%. The last, residue not exceed 5% and could not be less than 5%. After that, the reaction can be determined through calculation using the minimization of error method. Those calculation incorporates the chemical formula of raw material, the chemical formula of each product, and the stoichiometric coefficient of product. The reaction can be displayed or verified using spreadsheet that the total number of C, H, and O atom in in the raw material is equal to C, H, and O atoms in the products. The minimization of error can be said good if the error value is under 5%. In this study, the sum minimization of error was 0,31%. The formula used to determine the sum of errors can be written is as follows (Baskar and Ganesh, 2018).

$$\text{sum of error} = \frac{\text{Abs (value 1-value 2)}}{\text{value 1}} \times 100\% \quad (\text{Eq. 1})$$

After the rection mechanism was determined, the mechanism of reaction was inputted into HYSYS simulation to know all the obtained products. The mechanism was input as an equilibrium reaction and the conversion up to 100% (Asnawati et al., 2025).

2.2 Process boundary condition

The process boundary in this simulation includes pretreatment, reaction, and separation/purification units. Utility systems, storage, and supporting facilities are considered in economic evaluation but simplified in simulation model. Operating condition were defined based on laboratory experiments

2.2.1 Process simulation to produce bioavturbioavtur production

The process bioavtur production began. Ten tons per hour of RDBPO was pumped until 2 atm. Raw material was heated in a furnace that utilized the heat of product from the reactor until 350 °C (Ellzey et al., 2019). To produce biavture, the catalyst Co/Z-Mo/Z was employed in this reactor. In bioavtur production, the reactor has advantage because it was operated in low pressure and medium temperature, 1 atm and 323-350 °C. Based on experiment, the reactor needed 1% mass catalyst compared to the mass of raw material.

The model of the reactor was a conversion reactor because the mechanism of the reaction had been obtained. The product consisted of three main phases such as liquid, gas, and solid. The mixed product of liquid and gas was separated using three-phase separators (Ahmed et al., 2017). The gas phase was compressed with a centrifugal compressor into 12.5 atm then the product was separated between gas and liquid phases at 50 °C.

To optimize the product, the gas product from the separator is cooled into 20 °C, so bioavtur fraction can be restored and processed further in a distillation column. The liquid phases from the separator were processed further in three-phase separators to separate water from the liquid phase and solid phase. Liquid phase and biofuels fraction were mixed and sent to the distillation column with 12 trays in 12.5 atm. The distillation column is utilized to separate C5 below and C8 above. The top product was the LPG product. Then, the LPG product was stored in a sphere tank for 15 days. Bioavtur was enhanced from distillation column and was stored in a flat tank for 15 days or two weeks. The process is shown in Figure 1.

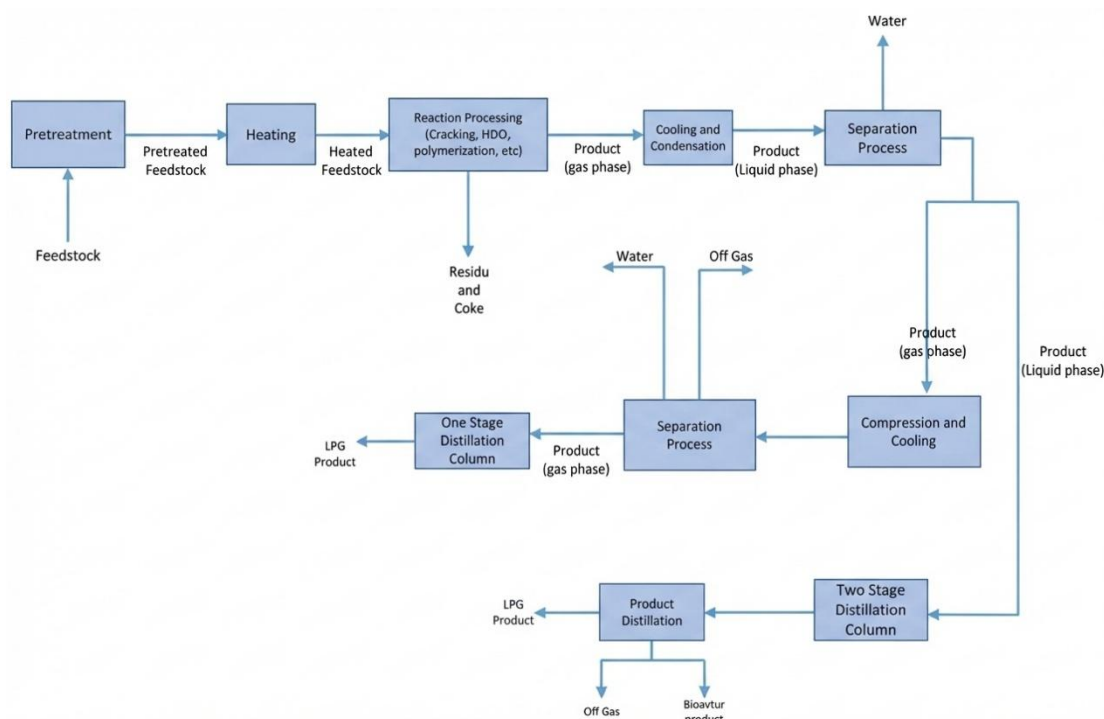


Fig. 1. Chemical processes to obtain bioavtur from RBDPO

2.2.2 Process simulation to produce biogasolinebiogasoline production

The process biogasoline production was started. Ten tons per hour of raw material was pumped until 4 atm. Raw material was heated in a furnace that utilized the heat of product from the reactor until 448 °C (Ellzey et al., 2019). To produce biogasoline, the catalyst Ni/Mo-ZSM-5 was employed in this reactor. In biogasoline production, the reactor has big challenge to overcome because it was operated in medium pressure and high temperature, 4 atm and 500-625 °C. The reactor needed 1% mass catalyst compared to the mass of raw material. The model of the reactor was a conversion reactor because the mechanism of the reaction had been obtained. The product consisted of three main phases such as liquid, gas, and solid. The mixed product of liquid and gas was cooled into 50 °C and separated using three-phase separators (Ahmed et al., 2017). The gas phase was compressed with a centrifugal compressor into 12.5 atm then the product was separated between gas and liquid phases at 46 °C.

To optimize the product, the gas product from the separator is cooled into 20 °C, so biogasoline fraction can be restored and processed further in a distillation column. The liquid phases from the separator were processed further in three-phase separators to

separate water from the liquid phase and solid phase. Liquid phase and biofuels fraction were mixed and sent to the distillation column with 10 trays in 11.5 atm. The distillation column is utilized to separate C5 below and C8 above. After that, the bottom product of column distillation is distilled in another column distillation (second distillation column) to enrich the bottom products and top product. The top product was the LPG product. That product was mixed with the LPG product from the LPG column (Al-Haj Ibrahim, 2014). Then, the LPG product was stored in a sphere tank for 15 days. Biogasoline was enhanced from the second distillation column and was stored in a flat tank for 15 days or two weeks. The process is shown in Figure 2.

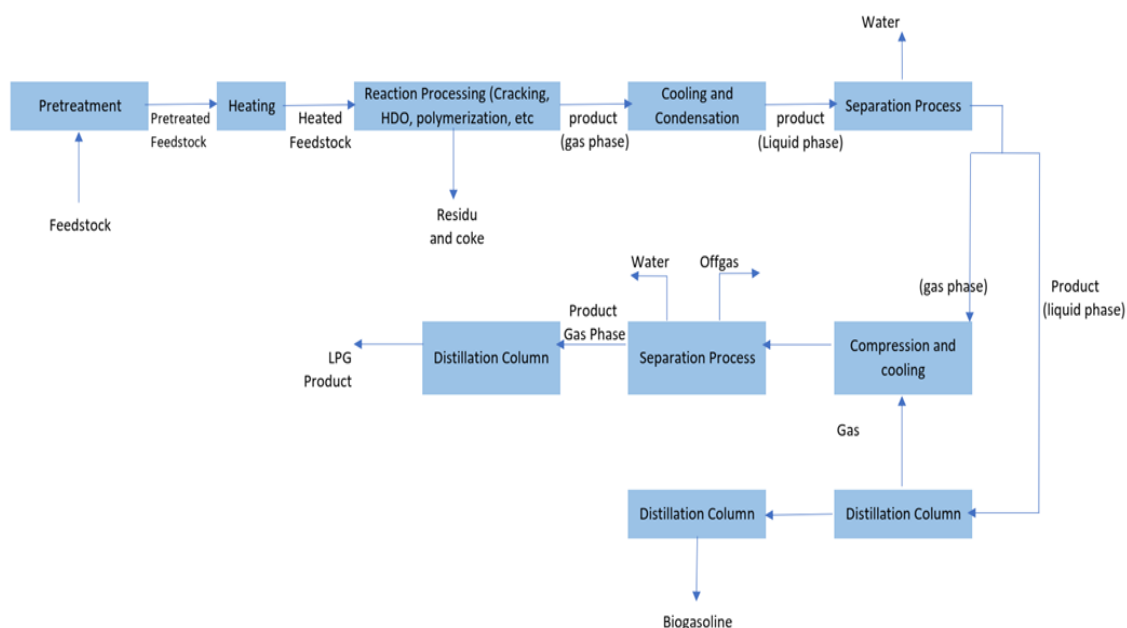


Fig. 2. Chemical processes to obtain biogasoline from RBDPO

2.3 Model validation

The simulation results were validated by comparing the product distribution with laboratory-scale experimental data, particularly for liquid, gas, coke and residue fractions. The simulation results follow experimental trends, although some deviation occurs due to limitation in component representation within the HYSYS database. In addition, atomic balance verification (C, H, and O) was performed to ensure consistency between input and output streams. The low error value (0.31%) confirms that the model is reliable for representing the process behavior.

2.3.1 The techno-economic analysis

The economic aspect can be evaluated to consider the feasibility studies of the plant. This study is used to compare the many indicators and determine whether the plant is feasible or not. There are some indicators that use to evaluate the plant. The indicators are internal rate of return and return time (Vilas Bôas et al., 2022). The IRR will be compared to minimum attractiveness rate (MAR) of Indonesia with minimal value 10%. Some costs in this study were referred to the Indonesian Policies. The total production cost and operating cost were calculated based on mass and energy balance that obtained from process simulation. The operating costs, calculated annually, consist of production cost, maintenance cost, utility cost, and solid waste disposal (Karimi et al., 2025). Production cost mainly consists of RBDPO as raw material, catalyst stock that should be replaced 1 – 2 per year, natural gas stock, utilities, and electricity. Maintenance cost can be calculated equal to 2% - 6% of fixed cost. Maintenance cost is represented by piping, infrastructure, and

materials that are needed for the maintenance and operation of the plant (Peters et al., 1991).

Table 2. The list of equipment cost

Equipment List	Equipment Code	Installed Equipment Price in Biogasoline (USD)	Installed Equipment Price in Bioavtur (USD)
Feed Tank	V-104	810,377	1,648,400
Biogasoline Tank	V-107	1,415,723	927,200
LPG Tank	V-105	3,369,533	3,190,091
Pump	P-100	79,685	40,000
	P-101	14,184	226,000
	P Column-01	94,800	43,388
	P Column-02	94,800	34,904
	P Column-03	94,800	32,332
Heat Exchanger and Air Cooler	P-Other Pump	107,378	263,136
	E-107	840,667	182,095
	FH-100/E-100	397,702	210,698
	E-101	18,603	131,760
	E-102	38,168	117,231
	E-103	95,320	276,004
	E-105	175,638	269,326
Three and Two-Phase Separator	V-100	99,300	100,300
	V-101	97,000	132,900
	V-102	69,000	
	V-103	69,000	69,000
	V-104	115,000	69,000
Reactor	V-105		100,000
	CRV-100	371,471	462,703
Compressor	K-100	2,353,885	2,830,901
	K-102	977,614	1,773,276
	Utilitas IA/PA	1,746,864	1,746,864
Column Distillation	T-100	254,200	219,200
	T-101	173,300	
	T-103	162,000	
Amount		14,136,012	15,096,710

Besides that, assurance is also included in this calculation for annual expenditure and include in operating expenditure. Value of assurance is 0.5% of Engineering Plant and Construction. The labor cost for this plant is shown in the table. The labor cost is based on Indonesia's Salary Policy. The plant capacity is designed for 10 tons/hour and the price of CPO is 525 USD/ton than in the market 802.5 USD. That price was considered with farm, shipping, and distribution costs. If the catalyst cost was calculated monthly, it would be equivalent to 47.388 USD/month. The side products from this plant were gas, residue, and coke. The equipment price can be provided from simulation using Aspen Capital Cost Estimator and the price that resulted from that software was customized with the Chemical Engineering Index. The price included installation cost for equipment (Øi et al., 2022). The equipment price is shown in Table 3, Not only the main equipment to produce biofuel, but also the refrigeration unit, dehydration unit, nitrogen plant, firefighting system, building, control room, road and fences, and general piping are also needed to support the plant. Besides that, to install the whole equipment into packages which had integrated into each other, some costs should be incurred. Table 3 shows the price to install the main equipment in both (biogasoline and bioavtur).

Table 3. The salary of each manpower as one of fixed operating cost

Component	Total	Salary (IDR)
Plant Manager	1	75,000,000
Planning & Production Manager	1	50,000,000
Engineering & Maintenance Manager	1	40,000,000
R&D and Lab Manager	1	25,000,000
GA Manager	1	20,000,000
Process Engineer	3	15,000,000
Mechanical Engineer	2	15,000,000
Instrument & Electrical Engineer	2	15,000,000
Environmental engineer	2	12,000,000
DCS Operator	6	7,000,000
Laboratory Analysis	3	4,000,000
Administration	2	5,000,000
OB	2	3,000,000
Driver	2	5,000,000
Finance	2	8,000,000

There are some differences in price of installed equipment between biogasoline plant and bioavtur plant. All reasons because of capacity in each equipment are different. Besides that, there are several differences in material equipment. But the main equipments are analogue to process vegetable oil into biofuels. Besides that, employees are needed to operate the plant. In this paper, the salary of employees called labor cost that represents the salary standard in Indonesia and particularly the salary standard in Gas and Oil Industries with several adjustments (Hays Oil & Gas, & Oil and Gas Job Search, 2012). In this table, salary standard is represented without allowances and bonuses. Table 4 show the basic salary of employee to run the plant.

Table 4. The list of many kinds of variable operating costs in bioavtur plant

Component	Unit	Consumption	Unit	Unit cost	References
variable cost					
CPO as Raw material	kg/h	10,000	USD/ton	525	calculation with policy consideration
Catalyst	Kg/2 years	150	USD/month	47,388	calculation with policy consideration
Natural Gas	MMBTU/h	11.87	USD/MMBtu	6	(Kementerian Energi dan Sumber Daya Mineral, 2022)
Chemicals for BFW			USD/m ³ biogasoline	6.79	
Electricity	kW	1,500	USD/kWh	0.0800	(Kementerian Energi dan Sumber Daya Mineral, 2016)
Cooling Water and Utility Process			USD/m ³ biogasoline	0.4296	(Aries & Newton, 1955)
Solid waste disposal			USD/m ³ biogasoline	0.00664	(Supriatini et al., 2019)
Bioavtur	/Litter	15,700	USD/ton	806	calculation with policy consideration
LPG	/Ton	16,000	USD/ton	734	calculation with policy consideration

Besides the salary of employee, this paper explains the operating cost. Table 4 and table 5 show the many kinds of variable costs.

Table 5. The list of many kinds of variable operating costs in biogasoline plant

Component variable cost	Unit	Consumption	Unit	Unit cost	References
CPO as Raw material	kg/h	10,000	USD/ton	525	calculation with policy consideration
Catalyst	Kg/2 years	150-200	USD/month	15,796	calculation with policy consideration
Natural Gas	MMBTU/h	16	USD/MMBtu	6	(Kementerian ESDM No.16, 2022)
Chemicals for BFW			USD/m ³ biogasoline	6.0900	calculation
Electricity	kW	2,736	USD/kWh	0.0800	
Cooling Water and Utility Process			USD/m ³ biogasoline	0.3303	(Aries & Newton, 1955)
Solid waste disposal			USD/m ³ biogasoline	0.0150	(Supriatini et al., 2019)
Bioavtur	/Litter	16,200	USD/ton	838	calculation with policy consideration
LPG	/Ton	20,000	USD/ton	919	calculation with policy consideration

The used material in this study mainly contains carbon steel. The main reason for using carbon steel is because it has a lower price than the other materials. Carbon steel is available in virtually all product forms, including pressurized form and shaped form. In addition, carbon steel can be used at high temperatures, the range is between 600 – 650 °C (Gandy, 2007). Besides that, carbon steel can be used in pressure 275 – 690 MPa. Based on that argument, Table 6 shows the many kinds of materials that are used in equipment manufacturing.

Table 6. The List of material equipment and number of equipment

Equipment list	Equipment code	Material in equipment of biogasoline	Material in equipment of bioavtur
Feed Tank	V-104	CS	CS
Biogasoline Tank	V-107	CS	CS
LPG Tank	V-105	SS304	SS304
Pump	P-100	CS	CS
	P-101	CS	CS
	P Column-01	CS	CS
	P Column-02	CS	CS
	P Column-03	CS	CS
	P-Other Pump	CS	CS
Heat Exchanger and Air Cooler	E-107	CS	CS
	FH-100/E-100	CS	CS
	E-101	CS	CS
	E-102	CS	CS
	E-103	CS	CS
	E-105	CS	CS
Three- and Two-Phase Separator	V-100	CS	CS
	V-101	CS	CS
	V-102	CS	
	V-103	CS	CS

Equipment list	Equipment code	Material in equipment of biogasoline	Material in equipment of bioavtur
Reactor Compressor	V-104	CS	CS
	V-105		CS
	CRV-100	SS304	SS304
	K-100	CS	CS
	K-102	CS	CS
Column Distillation	Utilitas IA/PA	CS	CS
	T-100	CS	CS
	T-101	CS	
	T-103	CS	

To determine fixed cost or fixed capital, many components should be inputted in the calculation. Physical plants consist of about 85 to 90 percent of total capital investment (Aries & Newton, 1955). Physical plant cost can be defined as the total cost of processing, installations, building, auxiliary service, and engineering involved in the development of the plant (León et al., 2020). Based on the source, EPC or Engineering, Procurement, and Construction consists of purchased equipment, installation, piping, instrumentation, insulation, electrical, building, land and yard improvement, and utilities (Dachyar et al., 2018). The total of that is direct plant cost. Total direct plant cost added with contractor's fee and contingency are called direct plant cost. The percentage of components in each fixed capital can be shown in Table 7.

Table 7. Component of capital investment and its percentage of fixed capital

Component of capital investments	Percentage of fixed capital
Purchased Equipment	25
Installation	11
Piping	10
Instrumentation	2
Insulation	2
Electrical	3
Building	8
Land and Yard Improvement	2
Utilities	9
Physical-plant cost	72
Engineering, Procurement, and Construction (EPC)	14
Direct Plant Cost (DPC)	86
Contractor's fee	4
Contingency	10
Fixed Capital	100
Working Capital	15
Total Capital Cost	Fixed Capital + Working Capital

To know the result from economic evaluation, there are some assumptions to make financial modeling. The result from the financial modeling such as net present value, internal rate of return, and many others. The assumption of 1 year is based on the Indonesia calendar that considers holidays. Financial modeling is the cash flow of money that represents all needed costs to develop and run a plant to achieve profit (Al-Thani, 2002). Table 8 shows us the assumptions that were used in this study and financial modeling.

Table 8. The assumption that used in financial modeling

Parameter	Assumption
Base year	2026
Operating hours per year	8,064
Loan amount	70%
Loan interest	30%

Parameter	Assumption
Loan term	10%
Working capital	6 %
Depreciation period	20
Utilization Plant Period	
Year 0	50%
Year 1	80%
Year 2	90%
Start-up time	3
Discount rate	12%
Income tax rate	25%

3. Results and Discussion

3.1 Mass and energy balance

In this result, this paper will compare the obtained liquid product using laboratory data and simulation data. From the laboratory data, the liquid product should be around 4,500 kg/h in Co/Z-Mo/Z catalyst. the simulation, the liquid product is dropped into 2,610 kg/h. In other hand, liquid obtained around 5400 kg/h from biogasoline plant. The results of Co/Z-Mo/Z have a big difference because of the minimization of error process that affects in reaction mechanism and several chemical compositions aren't in HYSYS databanks. The constraint in the process minimization to produce liquid products is range 40 – 55% for two catalysts. Co/Z-Mo/Z catalysts can obtain liquid until 40% and Ni/Mo-ZSM-5 can obtain until 55%. In addition, process separation during liquid production will make the result have big differences. There are some components C5 that are carried out to LPG fraction and there are some masses of liquid product wasted from three-phase and two-phase separators. This is the result of mass balance based on the minimization in HYSYS. Mass and energy balance of bioavtur are represented in Figure 3. Then, mass and energy balance of biogasoline are represented in Figure 4.

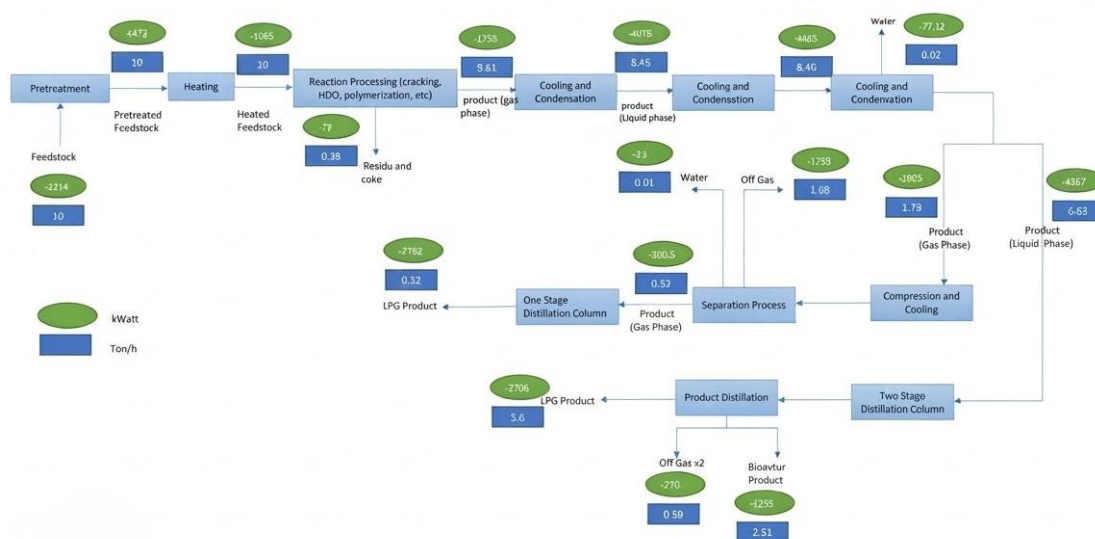


Fig. 3. Mass balance and energy balance of bioavtur production from RBDPO

From the simulation, we know that off-gas is also obtained. Off-gas contains a mixture of gases, such as carbon dioxide, carbon monoxide, methane, oxygen, and hydrogen (Crespo et al., 2023). The composition of this mixed gas is obtained from this process. That was necessary for conducting atomic balance C, H and O atoms across the process. In the process,

the off-gases are separated from the LPG product and liquid product. Laboratory data showed promising results, liquid products obtained 45% and gas products obtained up to 50%. After the simulation process, the obtained products dropped drastically, the obtained liquid product just reached 26% and the obtained gas product for LPG just reached 45%. And the residue and coke are more than 15% for Co/Z-Mo/Z catalyst. In other hand, biogasoline obtained from reactor in very optimal condition. Liquid product obtained up to 53% and LPG product up to 26%. This mainly happens because the model uses simplifications and limited components in Aspen HYSYS. Similar limitations in simulating complex biofuel systems have also been reported in previous studies This mainly happens because the model uses simplifications and limited component in Aspen HYSYS. Similar limitations in simulating complex biofuels system have also been reported in previous studies (Hafeez et al., 2021; Tao et al., 2017). From an industrial point of view, this lower liquid yield can reduce product output and profit. At the same time, it increases gas and residue production. However, the off-gas (carbon monoxide [CO], carbon dioxide [CO₂], methane [CH₄], and hydrogen [H₂]) can still be reused as fuel or energy source in the plant, which helps reduce operating costs and improve efficiency (Crespo et al., 2023). On the other hand, the biogasoline process shows better results, with liquid yield reaching 53%. This suggest that high-temperature cracking reactions are better represented in the model. Previous studies also show that higher temperature improves cracking efficiency and increases gasoline-range product (Wang et al., 2022).

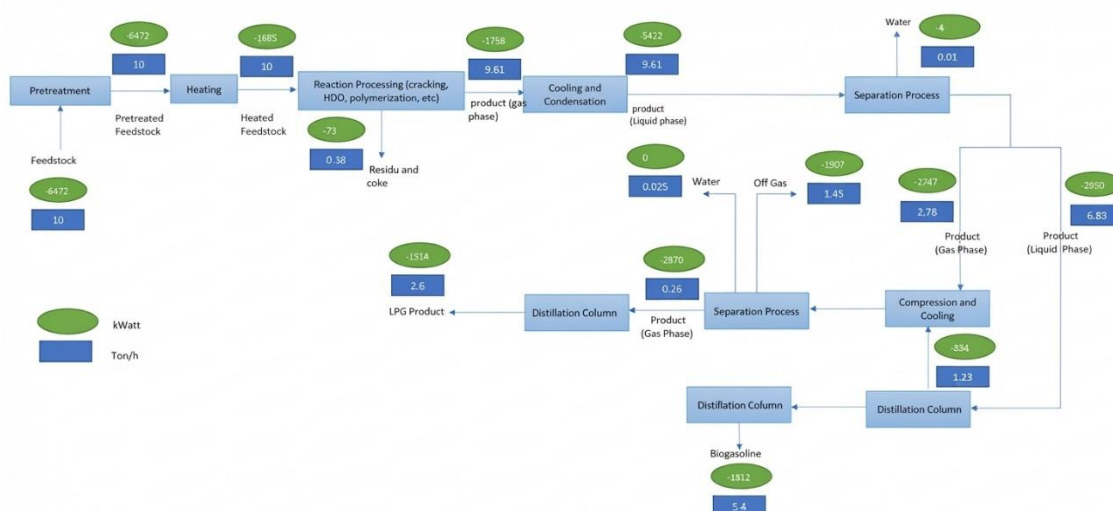


Fig. 4. Mass balance and energy balance of biogasoline production from RBDPO

3.2 Sustainability aspect

From a sustainability perspective, the biggest challenge is the raw material cost. About 77-82% of total operating cost comes from RBDPO. This shows that biofuel production is highly dependent on feedstock price, which is consistent with many studies (Karimi et al., 2025). In addition, using palm oil raises concern about competition with food supply. This issue has been widely discussed in biofuel sustainability studies (Chong et al., 2022). To improve sustainability, alternative feedstock such as used cooking oil or waste-based oils should be considered. Energy use is also important. The biogasoline process requires higher temperature (500-625 °C), which means higher energy consumption. This can increase emissions if fossil energy is used (Wang & Tao, 2016). Therefore, heat integration and renewable energy use are important to reduce environmental impact. By-product such as LPG and off-gas can give additional value. LPG can be sold, while off gas can be reduced. However, coke formation is still a problem because it can reduce catalyst performance and increase maintenance cost (Furimsky, 2000).

3.3 Economic analysis

The results of economic analysis are using obtained simulation data that applied in financial modeling. The used process of biofuel synthesis consists of simultaneous cracking, polymerization, hydrodecarboxylation. The process was supported with Co/Z-Mo/Z and NiMo-ZSM-5 catalyst in a packed bed reactor. Regarding the operating cost, there will be a distribution that is shown in table 9.

Table 9. Component of variable operating costs and its percentage of bioavtur plant and biogasoline plant

Component	Percentage of biavtur plant	Percentage of biogasoline plant
Variable operating cost		
Raw material	77.70%	82.14%
Catalyst	1.04%	0.37%
Natural Gas	1.04%	1.01%
Chemicals and others	0.60%	0.64%
Electricity	2.21%	1.72%
Maintenance	5.84%	4.58%
Process and wastewater	9.46%	7.68%
Solid waste disposal	1.09%	0.88%
Fixed operating cost		
Assurance	0.53%	0.46%
Overhead	0.50%	0.52%

In Table 9, fixed capital is the most needed cost to build this plant, it reaches up to 81%. The working capital in this plant is not bigger than land and yard improvement. This can happen because the plant is near an oil palm plantation. For most oil palm plantation plantations in peatland, processing and improving it is not as easy as ordinary land and it makes land and yard improvement need more cost. Land and yard improvement needs 7% of the whole total investment. Working capital does not take as big as land and yard improvement. A catalyst plant that produces the needed catalyst is assumed in Indonesia, and it gives an effect on the catalyst price. So, the catalyst price is not as expensive as an imported catalyst.

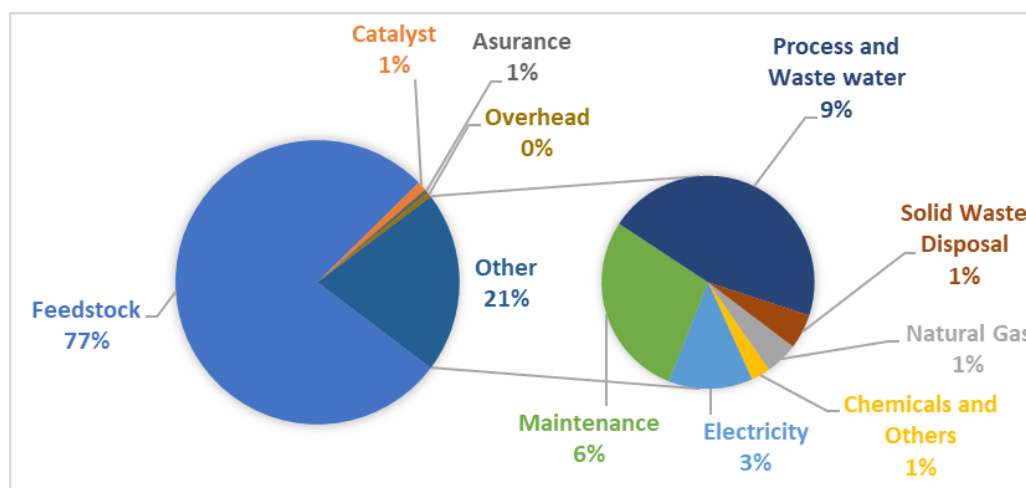


Fig. 5. Percentage of operating costs in process of bioavtur production

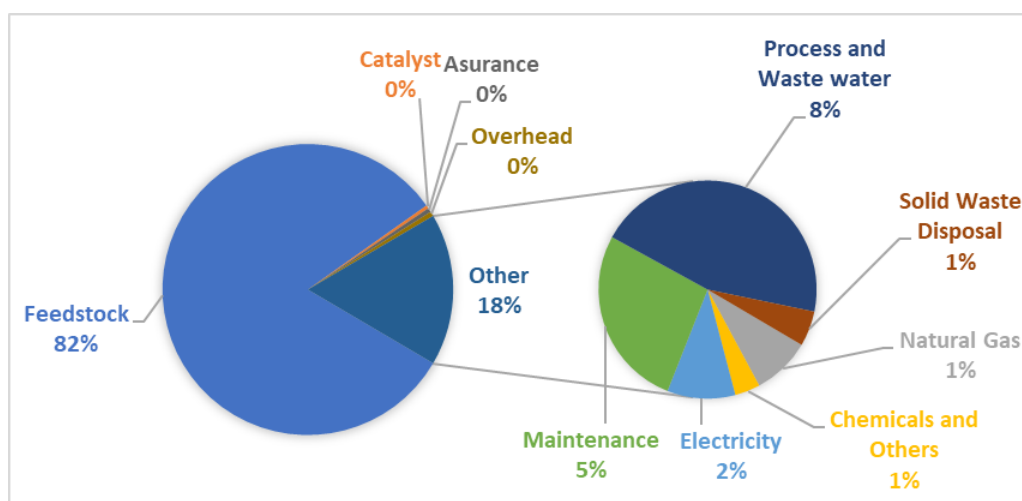


Fig. 6. Percentage of operating costs in process of biogasoline production

In general, operating costs can be divided into three sections, those are fixed cost, variable cost, and semi variable cost (Sinambela & Djaelani, 2022). Section one is fixed costs, consisting of raw material that is crude palm oil or raw material. Section two is variable operating cost that consists of natural gas, chemicals, and others, electricity, maintenance, process water, and waste treatment and catalyst. The last is semi variable costs consisting of assurance and overhead. That section is shown in Figure 5 and Figure 6. From Table 10., we know that raw material is the biggest cost among the others. To cover rawmaterial in the plant, almost 75% until 82% of the operating cost is used to provide raw material. Process and wastewater are the second largest after raw material, up to 9.5% of the operating cost is needed to prepare process water and utilize wastewater. Besides that, the operating value or working capital, fixed capital cost, and land and yard improvement can be known as its percentage.

Table 10. Percentage of fixed capital and working capital in bioavtur plant

Component	Cost (USD)	Cost (IDR)	Percentage
Fixed Capital	76,421,060	1,184,526,429,458	81%
Working Capital	6,487,559	100,557,157,761	7%
Land and Yard Improvement	11,354,839	176,000,000,000	12%
Total	94,263,457	1,461,083,587,219	100%

There are some others indicators to know is the study feasible or not. Break event point (BEP) is an indicator to evaluate the economic viability of each raw material by determining the gate fee needed to achieve cost neutrality. For bioavtur plant, BEP value is at point 59.52% of production. It means, at point 59.52% of production, plant is in neutral condition, there is no profit and no loss. For biogasoline plant, BEP value is at point 43.01% Besides break-even point, there is shut-down point. Shut down point is a condition which plant should stop its production. If it doesn't stop their production, it will get a loss. Bioavtur plant has shut down point at 9.8%. Besides that, Biogasoline plant has shut down point at 8.16%.

Table 11. Percentage of fixed capital and working capital in biogasoline plant

Component	Cost (USD)	Cost (IDR)	Percentage
Fixed Capital	75,139,622	1,164,664,350,000	81%
Working Capital	5,921,579	91,784,474,063	6,5%
Land and Yard Improvement	11,354,839	176,000,000,000	12,5%
Total	94,416,039	1,256,448,608,640	100%

3.4 Sensitivity analysis

3.4.1 Bioavtur plant

Sensitivity analysis is used in this study to know the most influential factor (Hussain, 2008). It will show us the effect into IRR value more than bank discount rate or the selling price based on Indonesia Policy. For Bioavtur plant, the parameters that use in this study are capital expenditure, raw material, or raw material price, bioavtur price, LPG price and electricity consumption. The raw material or raw material price varies in 5 values, 80 %, 90%, 100%, 110%, and 120% of raw material or USD 420, USD 473, USD 525, USD 578, and USD 630 respectively. The capital expenditure varies in 5 values, 80%, 90%, 100%, 110%, and 120% of base capital expenditure. The others, bioavtur prices (IDR 12,560; IDR 14,130; IDR 15,700; IDR 17,270; and IDR 18,840), LPG prices (IDR 12,800; IDR 14,400; IDR 16,000; IDR 17,600; and IDR 19,200), and electricity consumption (247.93; 278.92; 309.91; 340.90; and 371.89 kWh/m3 bioavtur). The sensitivity analysis of bioavtur is shown in Figure 7.

Figure 7. shows the result of the effect of fluctuating factors or we call it sensitivity chart for the production bioavtur from crude palm oil, in this study, RDBPO was used for that production. Toward the chart, bioavtur prices, LPG prices, and CPO prices have the significant effect of resulted in Internal Rate of Return (IRR). The obtained effect is positive and negative to IRR. For the effect of CPO prices, increasing the CPO price from USD 420 to USD 630 has bad influences on IRR. If CPO prices increase, the value of IRR will decrease, lower than the bank discount rate. It will be different if LPG prices and bioavtur prices increase. The increase in those product prices has a good influence on IRR. The price of LPG and bioavtur price make the IRR value increase. This is a good condition because if the IRR is more than the bank discount rate, it will attract the investor to invest their money. Besides that, the effect of the maintenance price and catalyst price is not as significant as the raw material price and product price. From the graph, we know that highly sensitive factors are bioavtur price, LPG price, and CPO price. Raising the CPO price from USD 473 to USD 525 raised the IRR from 12.21 % to 15.55%. The product price also has a great impact on attracting investors. Raising the price of bioavtur from IDR 15,700 to IDR 17,270 raised the IRR from 12.21% to 16.16%.

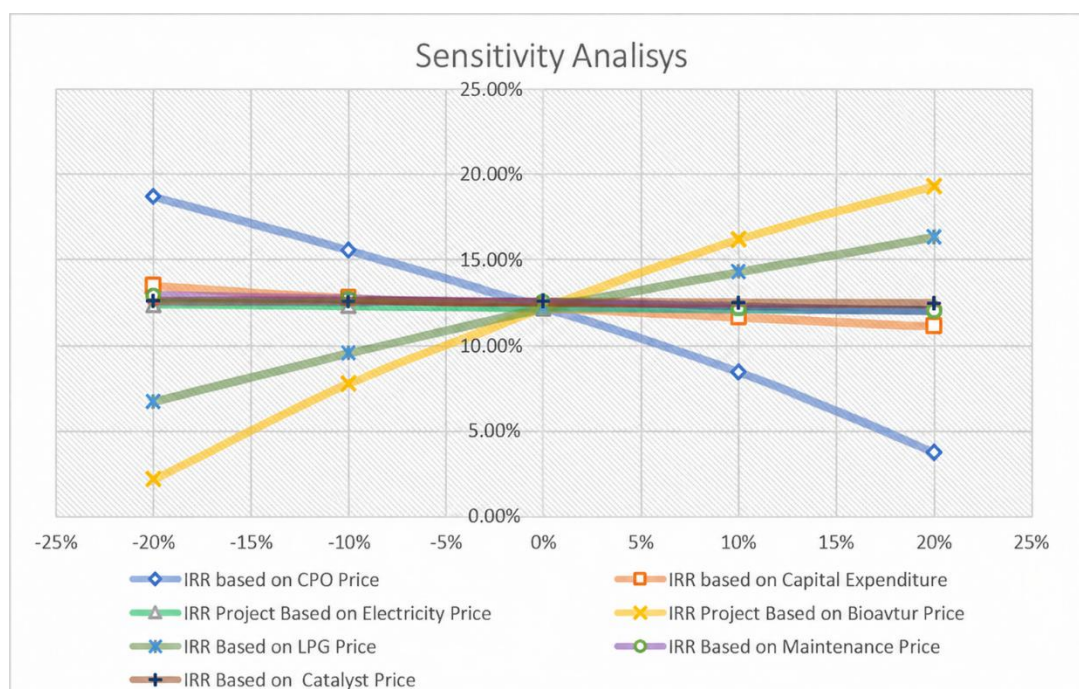


Fig. 7. Sensitivity analysis of bioavtur production from RBDPO

3.4.2 Biogasoline plant

For Biogasoline plant, the parameters that use in this study are capital expenditure, raw material, or raw material price, bioavtur price, LPG price and electricity consumption. The raw material or raw material price varies in 5 values USD 420, USD 472.5, USD 525, USD 577.5, and USD 630 respectively. The capital expenditure varies in 5 values, 80%, 90%, 100%, 110%, and 120% of base capital expenditure. The value is USD 60,991,972; USD 68,615,969; USD 76,239,965; USD 83,863,962; and USD 91,487,959. The others, biogasoline prices (IDR 12,960; IDR 14,580; IDR 16,200; IDR 17,820; and IDR 19,440), LPG prices (IDR 16,000; IDR 18,000; IDR 20,000; IDR 22,000, and IDR 24,000), and electricity consumption (163.36; 183.78; 204.20; 224.62; and 245.04 kWh/m³ bioavtur). The sensitivity analysis of biogasoline is shown in Figure 8.

Figure 8, shows the result of the effect of fluctuating factors or we call it sensitivity chart for the production biogasoline from crude palm oil, in this study, RDBPO was used for that production. From the chart, biogasoline prices, LPG prices, and CPO prices have the significant effect of resulted in Internal Rate of Return (IRR). The obtained effect is positive and negative to IRR. For the effect of CPO prices, increasing the CPO price from USD 420 to USD 630 has bad influences on IRR. If CPO prices increase, the value of IRR will decrease, lower than the bank discount rate. It will be different if LPG prices and bioavtur prices increase. The increase in those product prices has a good influence on IRR. The price of LPG and biogasoline price make the IRR value increase. This is a good condition because if the IRR is more than the bank discount rate, it will attract the investor to invest their money.

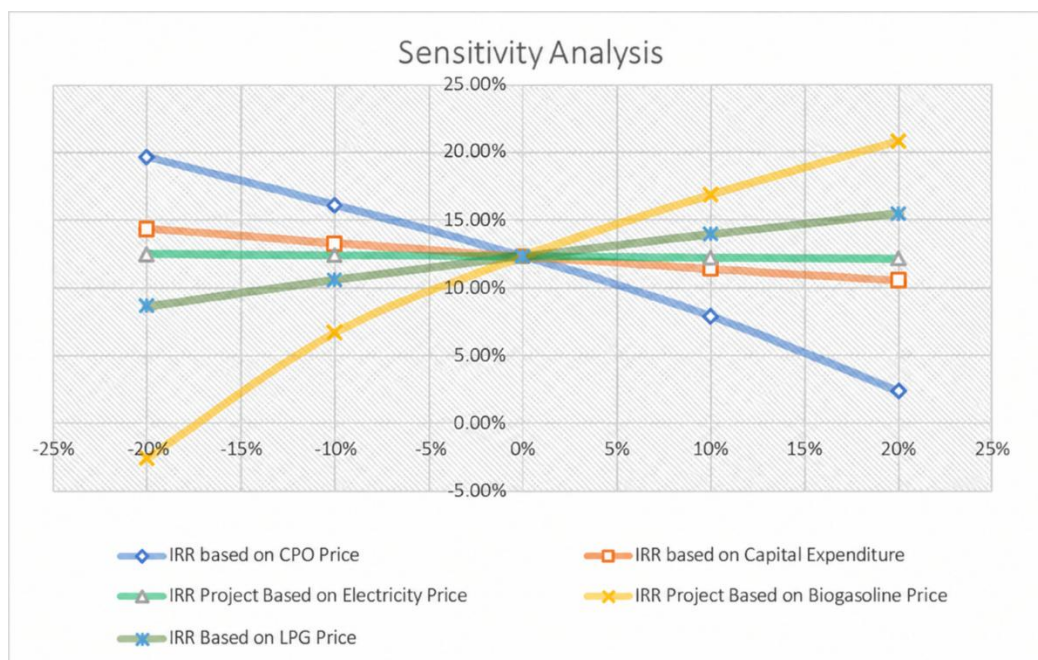


Fig. 8. Sensitivity analysis of bioavtur production from RBDPO

From the graph, we know that highly sensitive factors are bioavtur price, LPG price, and CPO price. Raising the CPO price from USD 473 to USD 525 lowered the IRR from 19.64 % to 12.30%. The product price also has a great impact on attracting investors. Raising the price of bioavtur from IDR 16,200 to and IDR 19,440 raised the IRR from 12.34% to 20.84%. From the two sensitivities analysis, reader will know that three factors give big impact. The capital expenditure and electricity do not give significant effect in the sensitivity analysis. It can be seen in figure 6 and figure 7 that the slope of the two are not big enough. It's different with sensitivity analysis due to raw material and product. The slope is bigger than electricity and capital expenditure.

3.5 Industrial feasibility

Both processes show good economic potential based on IRR values. However, profitability is very sensitive to raw material price. This is in line with previous techno-economic studies (Pearlson et al., 2013; Vilas Bôas et al., 2022). The biogasoline process has better economic performance, with higher IRR and lower break-event point. This means it is more flexible and less risky under changing market conditions. Similar findings are reported in other studies comparing fuel pathways (Wang et al., 2022). However, the biogasoline process operates at higher temperature and pressure, which increases equipment cost and operational complexity. In contrast, the bioavtur process operates at milder conditions, which can improve stability and reduce operational risk (Elliott, 2007).

4. Conclusions

This study evaluated techno-economic feasibility of biofuel production from RBDPO through two pathways, namely bioavtur and biogasoline, using process simulation and economic analysis. Bioavtur and biogasoline produced using different catalyst. Catalyst Co/Z-Mo/Z is used to produce bioavtur and Ni/Mo-ZSM-5 is used to produce biogasoline. Both bioavtur and biogasoline are produced by complex reaction, like hydrodecarboxylation, hydrodeoxygenation, cracking, and polymerization. The results show that both pathways are technically feasible and economically promising, although they have different strengths and limitations. To model the complex reaction and to know the mechanism of reaction, mass balance and minimization of error are employed to know the stoichiometric coefficient in the product. After knowing the mechanism of reaction, value of product and equipment of processes can be determined based on laboratory experiment. Then, financial modelling can be applied to determine various indicators of whether a plant is feasible to establish or not. Comparison between: bioavtur and biogasoline are feasible to establish or not are determined by various indicators. The biogasoline pathway shows better economic performance, with higher liquid yield, higher IRR, and lower break-event point. This indicates that it is more attractive for industrial implementation under current market conditions. On the other hand, the bioavtur pathway operates under milder conditions and has strategic importance for supporting the development of sustainable aviation fuel.

The most significantly affecting is internal rate of return or IRR. The IRR of two plants is good enough. Both bioavtur plant and biogasoline plant have of twice than the deposit interest rate. It means that two plants are feasible to establish. But there is something should be done before the establishment. That was product quality testing on a larger scale compared to laboratory scale. In addition, this study shows that process integration, energy efficiency, and by-product utilization (such as LPG and off-gas) are important factors in improving both economic and environmental performance. These aspects are essential for supporting cleaner and more efficient biofuel production systems. Overall, this study provides practical insight into the design and evaluation of biofuel processes and support the ongoing transition toward renewable and low-carbon energy systems. Future work should focus in improving model accuracy, optimizing process conditions, and integrating more sustainable feedstocks to enhance the role of biofuels in the global energy.

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Author Contribution

S. K.: conceptualization, methodology, reaction pathway analysis, laboratory data analysis, process simulation using Aspen HYSYS, techno-economic and financial analysis, interpretation of results, manuscript drafting, critical revision, and final approval of the manuscript.

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Declaration of Generative AI Use

During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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