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TECHNO-ECONOMIC ANALYSIS OF BOILER WASTE HEAT-BASED BIOMASS DRYING SYSTEM OF A COAL COFIRING POWER PLANT

Mahpudi Baisir [1], Adi Surjosatyo [2] ✉, Hafif Dafiqurrohman [3]

[1]) **Department of Energy Systems Engineering**
Faculty of Engineering
University of Indonesia
Depok, Jawa Barat 16424, Indonesia

[2]) **Department of Mechanical Engineering**
Faculty of Engineering
University of Indonesia
Depok, Jawa Barat 16424, Indonesia
adi.surjosatyo@ui.ac.id;
adisur@eng.ui.ac.id;
adisur11@gmail.com

[3]) **Tropical Renewable Energy Center**
Faculty of Engineering
University of Indonesia
Depok, Jawa Barat 16424, Indonesia
mahpudi.baisir21@office.ui.ac.id

Abstract

This research aims to find the optimal operating pattern in a rotary dryer type biomass drying system with the heating medium from exhaust gas leaving the boiler. This heating medium is believed to provide high profits because it does not require additional energy. However, the lowest moisture may not necessarily provide maximum investment profits due to trade-offs with capital and operational costs. The research results show that the test point at a biomass inlet flow of 10 t/h, a residence time of 25 minutes, and an exhaust gas flow of 90 t/h can optimally obtain the highest three investment parameters, including USD 8,518,085.33 for NPV, 150.32% for IRR, and 0.67 years for PBP. So that it succeeds in reducing the biomass moisture from 44.57% to 10.90%. Reductions in energy output and operational duration should be avoided wherever possible because they have a significant impact on reducing profit.

Keywords: *Biomass, Flue Gas, Investment, Moisture Content, Rotary Dryer.*

1. INTRODUCTION

Every Indonesian coal-fired power plant (CFPP) strives to increase the utilization of biomass energy to boost the renewable energy mix. Cofiring has been increasingly implemented since around the 2020s. However, various technical obstacles are still encountered in its implementation, including slagging and fouling, increased oxidation rates in boiler pipes, high moisture content in utilized biomass, and so on. This study focuses on the problems that arise due to the high moisture content of biomass used as feedstock for cofiring. The level of moisture affects the calorific value, requiring extra procedures on the biomass before use. Praevia and Widayat applied the hydrothermal treatment (HT) technique to improve the quality of empty oil palm bunches (EFB) biomass by torrefaction, which involved heating the EFB at 300 oC for 15 to 60 minutes. Using this, they were able to decrease the nitrogen and sulphur content while raising the calorific value from 7.86 MJ/kg to 22.22 MJ/kg, which is nearly identical to coal's calorific technique value of 22.34 MJ/kg [1].

Pure or untreated pellets are susceptible to moisture and can lead to considerable issues during shipping, storage, and handling. They are rapidly damaged when exposed to water [2]. Craven et al. observed that pure pellets rapidly expanded after being immersed in water for only 30 seconds. Furthermore, the pellets disintegrated in less than 600 seconds [2]. Before

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✉ **Adi Surjosatyo**
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the combustion process, moist biomass requires more energy for water evaporation. The energy that should be allocated for heat generation is redirected to remove unnecessary moisture. Orang and Tran conducted observations on the combustion characteristics of an experimental furnace integrated with a camera. The empirical findings demonstrated that specimens with a moisture content of 40% were still sensitive to ignition and burned easily at 800 °C, but needed a longer ignition time at 500 °C and no ignition at all at 400°C [3]. Another issue arises from the possibility of fire occurring during the storage of biomass with high moisture content. A comprehensive experimental study was conducted by Chen et al. to investigate the impact of moisture content on the self-heating of stored biomass. This study demonstrates that enhancing the moisture content of wheat straw and rice straw could significantly improve the rate of oxygen consumption, an effect of microbial activity. This is demonstrated by the rise in oxygen consumption in the experimental container, which increases by a factor of 2 to 3 as the water content gradually increases from 20% to 95%. It is interesting that the highest temperature in the experiment remains within the range of 46.5ºC [4]. Wet biomass is also related to its flowability. This is important because most biomass utilization in cofiring technology has to pass through a grinding process in the coal mill. A study conducted by Chen et al. attempted a series of experiments to determine how the moisture content of straw affects the flow behavior of a binary straw-coal granular system. The experiment reveals a complex relationship between water content and internal friction angle. Initially, as water content increases, the internal friction angle decreases, but then increases and finally decreases until it reaches a minimum value at a water content ranging from 8% to 10%. However, this experiment has already demonstrated a negative impact of biomass moisture on flow rate [5].

Several treatments have been proposed for dealing with the moisture content of biomass raw materials prior to utilization. There are two popular methods for drying biomass: mechanical drying and thermal drying. Each entity possesses distinct characteristics and objectives. Mechanical drying is usually used to remove high moisture content, or more than 50%. Afterwards, thermal drying is utilized to achieve significantly lower moisture levels [6]. Various mechanical drying methods, such as filters, screens, presses, vacuums, or centrifuges, can rapidly decrease moisture content to below 50%, depending on the specific materials and specifications of the drying equipment installed [7]. Thermal technology offers a wide range of drying methods, such as rotary dryers, conveyor dryers, flash or pneumatic dryers, fluidized bed dryers, microwave dryers, superheated steam dryers, and others [7]. In addition, this thermal drying technology offers a specific approach, such as the torrefaction technique solution at EFB, which has been implemented [1].A specific technique that combines multiple heat energy sources has been explored. In this technique, waste heat from a 100 MW plant is utilized. The waste heat comes first from hot water at a temperature of 90oC. Then, it is further heated by exhaust gas at a temperature range of 250–450 oC. This process results in the production of superheated steam with a temperature of 140–180 oC, which is subsequently used as a medium for drying biomass. Nevertheless, it employs a dryer with a conveyor belt design and utilizes steam as the heating medium, which is heated by the waste heat generated from the boiler's flue gas exit. Similarly, the expense of drying employs the “Lang” factor as a basic metric for computing cash flow and NPV [8].

In Indonesia, direct co-firing is the dominant technology for combining biomass with coal. This involves directly blending the two fuels at the coal yard and coal bunker areas using heavy machinery [9, 10]. Typically, biomass sourced from nearby suppliers is delivered to the facility using sacks and open-bed vehicles. The storage of biomass and a significant portion of the mixing process in the coal yard area also occur outdoors, leaving them vulnerable to rain exposure. This indicates that it must be difficult to consistently maintain the moisture content of the biomass during transportation and storage. This, in turn, leads to a rise in the moisture content of the co-firing fuel combination before it is transferred to the combustion boiler. The high hygroscopicity of biomass leads to the potential absorption of significant quantities of water. Presently, the biomass drying procedure conducted in CFPPs remains relatively unpopular, as the majority of facilities in Indonesia only began implementing co-firing in 2020. Implementing a drying procedure prior to use yields numerous benefits. Possible outcomes involve improving combustion efficiency in the boiler, simplifying transportation logistics, and maximizing flow capacity.

This study aims to develop a drying apparatus that is optimal for the biomass resources at hand in order to achieve maximum drying efficiency with little investment prior to its utilization in a CFPP. The heating medium utilizes waste heat from the flue gas exiting the boilers, resulting in no fuel expenditures for the dryer. Nevertheless, it needs to be balanced out by the substantial upfront expenditure required for the drying equipment, which incorporates high-quality components. It is expected that this research can serve as a reference for improving the efficiency of biomass utilisation through cofiring technology in CFPPs in Indonesia as part of energy conservation efforts. Furthermore, it is expected that most CFPPs will progressively increase the proportion of biomass utilisation and optimise their energy conversion, eventually shifting to the exclusive use of pure biomass as fuel. Thus, it is expected that each CFPP can extend its operating life because it has actively contributed to the implementation of clean and environmentally friendly energy.

2. METHOD AND MATERIAL

2.1. Power Plant and Biomass Specification

This research was carried out at a CFPP located in Indonesia. This power station is in a coastal region adjacent to the sea. In the northern region, there is a stretch of energy plantation forest covering an area of approximately 4600 hectares, with a radius of up to 100 kilometers. This forest has a total potential biomass of over 165 thousand tons per year. It is expected that this biomass can be used as a long-term source of feedstock for power plant. The system consists of three CFPP units that are similar to one another with capacity of 3 x 350 MW. Implemented initial cofiring since around the end of 2020, with a composition that remains below 3%. The facility utilizes a mixture of sawdust and rice husk in a ratio of around 90:10, which is sourced from local suppliers. According to the data collected from the field, it was discovered that the biomass provided had a high moisture content of around 44.57% and a calorific value of 2673.72 kcal/kg.

Table 1. Specification of CFPP.

Specification of CFPP	
Type	Steam Coal Power Plant
Installed Capacity	3 x 350 MW
Boiler	Pulverized Coal
Fuel	Coal - Biomass
Coal Consumption	600 t/h
Biomass Consumption	200 t/day
Type of Coal	Low Rank (4000-4400 Kcal/Kg) and Medium Rank (4500-5000 Kcal/Kg)
Type of Biomass	Approximately 90% Sawdust : 10% Rice Husk

Figure 1. Sample of wet biomass.

Due to the unpredictable nature of biomass receipts, the quantities received typically align with the supplier's capabilities. The data provided is presumed to represent the daily average. Based on information obtained from sources at the plant site, it appears that the adoption of rice husks as a fuel source is generally quite low. As a result, the majority of power plants use sawdust biomass, with an average composition of 90% sawdust and 10% rice husks. Thus, the composition of the mixture of biomass can be determined using the Eqs. (1), (2) and (3). The biomass blending data to be used in the Aspen simulation may be found in Table 3.

$$\overline{Moist_{bl}} = \frac{(\overline{\%Rec_{rh}}\ x\ \overline{Moist_{rh}}) + (\overline{\%Rec_{sw}}\ x\ \overline{Moist_{sw}})}{\overline{\%Rec_{rh}} + \overline{\%Rec_{sw}}} \quad (1)$$

$$\overline{LHV_{bl}} = \frac{(\overline{\%Rec_{rh}}\ x\ \overline{LHV_{rh}}) + (\overline{\%Rec_{sw}}\ x\ \overline{LHV_{sw}})}{\overline{\%Rec_{rh}} + \overline{\%Rec_{sw}}} \quad (2)$$

$$\overline{Comp_{bl}} = \frac{(\overline{\%Rec_{rh}}\ x\ \overline{Comp_{rh}}) + (\overline{\%Rec_{sw}}\ x\ \overline{Comp_{sw}})}{\overline{\%Rec_{rh}} + \overline{\%Rec_{sw}}} \quad (3)$$

Table 2. Biomass receipt samples.

No.	Date	Type	Vehicle No.	Quantity (kg)	Sampling test		Sizing	
					Moisture (%)	Calorific Value *ARB (kcal/kg)	+ 5 mm (%)	- 5 mm (%)
1	17-Aug-23	Rice Husk	4	15040	71.23%	883.00	0.3	99.7
2	18-Aug-23	Rice Husk	11	63210	54.82%	1471.00	0.7	99.3
3	19-Aug-23	Rice Husk	26	153340	77.37%	686.00	0.2	99.8
4	20-Aug-23	Rice Husk	25	133280	62.90%	1215.00	0.8	99.2
5	21-Aug-23	Rice Husk	32	192280	64.16%	1176.00	0.3	99.7
Average					**66.10%**	**1086.20**	**0.46**	**99.54**
1	08-Dec-23	Sawdust	19	161480	38.42%	2996.00	0	100
2	09-Dec-23	Sawdust	11	99380	46.57%	2664.00	0	100
3	10-Dec-23	Sawdust	15	122650	39.97%	2930.00	0	100
4	11-Dec-23	Sawdust	15	129210	45.60%	2765.00	0	100
5	12-Dec-23	Sawdust	19	138140	39.80%	3082.00	0	100
6	13-Dec-23	Sawdust	15	108290	39.26%	2956.00	0	100
7	14-Dec-23	Sawdust	25	196500	47.85%	2571.00	0	100
8	15-Dec-23	Sawdust	28	217810	39.93%	2938.00	0	100
Average					**42.18%**	**2862.75**	**0**	**100**

Table 3. Proximate/Ultimate analysis.

Parameter	Rice Husk	Sawdust	Blending
Calorific Value (Kcal/Kg)	1067.62	2852.17	2673.72
Proximate Analysis (%)			
Moisture Content (MC)	66.10	42.18	44.57
Volatile Matter Content (VM)	61.70	79.18	77.43
Fixed Carbon Content) (FC)	20.15	19.10	19.21
Ash Content (Ash)	18.15	1.72	3.36
Ultimate Analysis (%)			
Nitrogen Content (N)	0.32	0.50	0.48
Oxygen Content (O)	32.05	37.70	37.14
SulphurContent (S)	0.08	0.02	0.03
Ash Content (Ash)	18.15	1.72	3.36

2.2. Material Selection for Dryer System

Using the waste from the boiler's flue gas as a heat source for biomass drying systems can significantly reduce operational costs. However, it is essential to carefully select the material for each piece of equipment to guarantee its resistance against corrosion induced by the flue gas. It is believed that the presence of chlorine, sulphur, potassium, and sodium in fuel can enhance oxidation on the surface of the metal when it comes into contact with flue gas [11]. Zuo et al. found that when the temperature of the exhaust gas falls below the acid dew point (ADP), the condensation of acid, typically sulfuric acid (H_2SO_4), can take place. The melting point of H_2SO_4 is about 500–600 ºC, and it fully melts at 200ºC [12]. The acid condensation will accelerate the process of oxidation, commonly referred to as low-temperature corrosion (LTC). Typically, the exhaust gas is maintained at a higher temperature than the ADP to prevent corrosion of the material.

The topic of selecting materials that can withstand exposure to flue gas has been extensively studied in many literary works. DSS 2205 is regarded as a suitable material for withstanding oxidation when exposed to flue gas. It has a very low mass loss rate of only 0.13 µm/y at a temperature of 320°C [13]. Ghosh suggests the utilization of steel alloys including chromium (Cr), nickel (Ni), molybdenum (Mo), and copper (Cu) in generator boiler tubes. For instance, the use of SUS310S is recommended to achieve a longer lifespan compared to the utilization of SA 210 Gr. A1, which experiences accelerated corrosion [14]. Lie and Zeng categorized steel-based materials based on their resistance to corrosive flue gas environments. They began with the category of "Carbon Steel," which exhibited the lowest resistance to rust. This was followed by "Ferritic Steel," which contains chromium to enhance its resistance to oxidation. Next, the addition of chromium (Cr) and nickel (Ni) components to "Stainless Steel" makes it an alloy steel that is superior to ferritic steel in its ability to resist oxidation in flue gas conditions. Lastly, "Nickel-based Alloy" is the material with the highest resistance to oxidation [15]. Based on the evidence, it can be inferred that Ni-based alloy is the optimal selection for a steel alloy, with stainless steel being the second-best option for resisting corrosion rates, particularly in situations with elevated acid levels.

Based on the market research conducted, it has been found that the cost of nickel-based alloys is significantly higher compared to stainless steel, with a difference of 10 times. In addition, it can be quite hard to find pipes that have dimensions suitable for the nickel-based alloy material. Meanwhile, there is a wide availability of stainless steel in various sizes, including large pipes and plates. Although it is more expensive than carbon steel, with a price that is roughly 3 to 4 times greater. Stainless steel is the optimal choice for the dryer design in this research. From the market research and material calculations, the total of an additional biomass drying system with a capacity of 200 t/d including the piping system at this CFPP is USD 804,558.02.

2.3. Flue Gas Stream and Tapping Point

Flue gas from boilers is considered a cost-effective heating source for dryer operations. In this research, the exhaust gas collection point was determined at the Induction Draft Fan unit 1 (IDF #1) outlet. The necessary pipeline is approximately 2 x 500 meters in length to connect the flue gas collection point at IDF #1 outlet to the dryer placement location in the coal yard area. The pipeline then returns to the chimney for expansion, as shown in the illustration below. The flue gas is then directed back to the boiler area for disposal through the chimney, mixed with the flue gas emitted by other boilers. The purpose of this is to prevent the need for constructing a new chimney at the drier site, which requires high construction and a strong concrete structure. Additionally, it would require obtaining licenses for environmental concerns, despite the fact that the quantity of flue gas remains unchanged with the addition of this dryer. The necessary action is to install an extra pipeline for the flue gas line, with the same length as the input flue gas pipe.

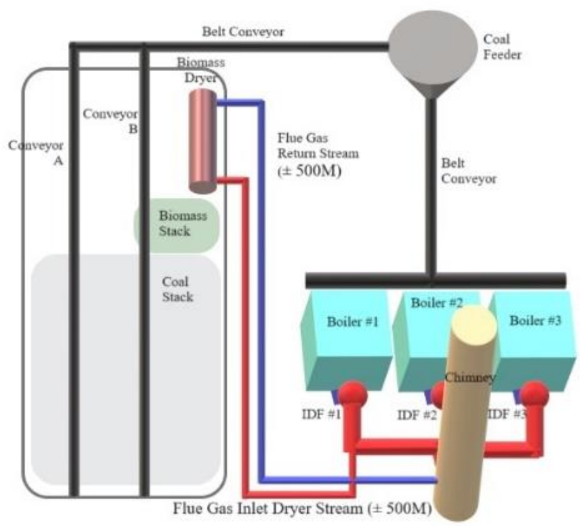

Figure 2. Illustration of power plant and dryer system layout.

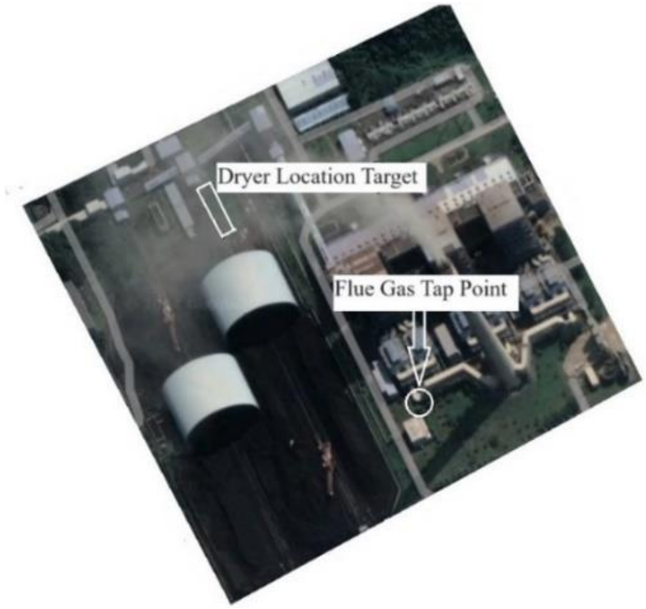

Figure 3. Illustration of layout via satellite [16].

Another challenge is that the IDF (Induced Draft Fan) outlet pressure for each boiler is very small, in the range of 0 to 20 Pa. This is because the furnace operates at negative pressure (-3000 Pa), so an additional centrifugal fan is needed which is installed after the tapping point. This additional centrifugal fan also results in high additional operational costs from the use of electric power. The quantity of flue gas produced from the combustion of each boiler is very large, so it is considered more than enough to be used as a heating medium in dryers, which is only less than 10% of ± 1200 t/h of flue gas per boiler with a temperature of around 150 ºC. The outlet pressure of a centrifugal fan is determined by how large the pressure drop occurs along the pipe using Darcy-Weisbach Equation. After running multiple simple simulations using this equation, the dimensions of the exhaust gas distribution pipe are determined to be 24" so that the centrifugal fan's additional outlet pressure is still accommodated.

Table 4. Additional fan requirements based on pressure loss.

Parameter	Unit	Flue gas flow (t/h)		
		70	80	90
Pipe dimension	inch	24	24	24
Total of head loss	Pa	4727.97	6123.81	7699.25
Additional fan efficiency	%	0.6	0.6	0.6
Additional fan shaft power	kW	181.41	268.54	379.83

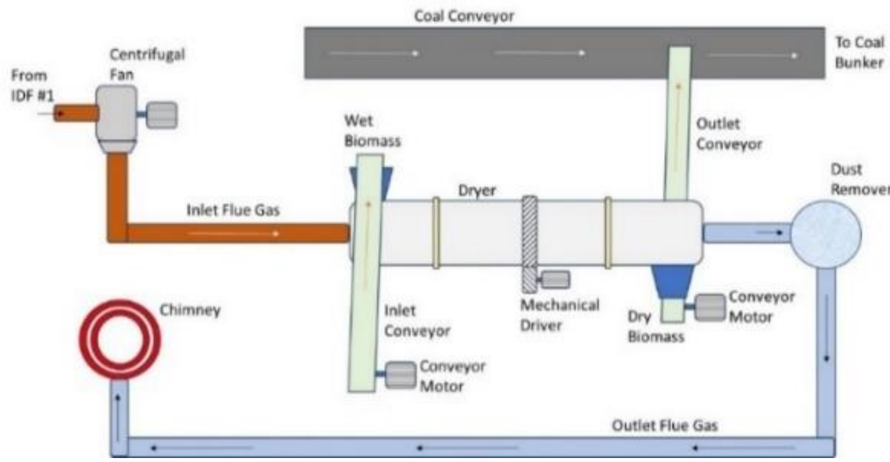

Figure 4. Schematic Diagram of Biomass Drying System Using Waste Flue Gas.

2.4. Dryer System Modelling Simulation Using Aspen Plus

The Aspen Plus simulation was utilized to gain a comprehensive analysis of the operational conditions, heat transfer, and evaporation processes in the drying system. An advantage of utilizing Aspen Plus is its ability to simulate process flow that involves non-conventional (NC) components such as biomass. The IDEAL type is chosen in the base technique column to set the standard way to compute the model. This makes sure that all equilibrium calculations are done using the ideal gas law, Raoult's law, or Henry's law [17]. The selected stream class for this simulation is MIXNCPSD, which considers the presence of solid non-conventional material (NC), such as biomass, and also the particle size distribution (PSD). Aspen Plus offers a variety of solid dryer models, such as spray, flash, fluidized bed, conveyor, and finally a rotary drum, which were selected for this investigation.

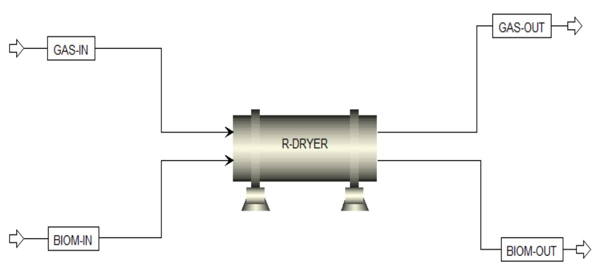

Figure 5. Biomass dryer simulation design.

In this study, three different biomass flow rates, 8 t/h, 9 t/h, and 10 t/h, will be utilized to identify the most optimal design parameters. The moisture content of the biomass will stay at 44.57% wb. The flue gas flow rate will be used at three different values: 70 t/h, 80 t/h, and 90 t/h. The residence time will be used for three different durations: 15 minutes, 20 minutes, and 25 minutes.

Table 5. Simulation parameter.

Aspen Parameter	Value
Gas Inlet	
Temperature	150 ^{o}C
Pressure	1 bar
Flow	**Experiment Variables 70, 80 and 90 t/h**
Biomass Inlet	
Temperature	25 ^{o}C
Pressure	1 bar
Flow	**Experiment Variables 8, 9 and 10 t/h**
Moisture Content	44.57 % wb
Dryer Block	
Operation Mode	Continuous
Dryer Type	Convective Dryer
Gas Flow Direction	Co-Current
Length of Dryer Dimension	12 meter
Solid residence time	**Experiment Variables 15,20 and 25 minutes**
Solid moisture content basis	Dry
Critical drying rate	0.2
Equilibrium drying rate	0.07

This rotary dryer is highly susceptible to fire threats due to its convection design. Co-current is often regarded as safer than counter-current because it ensures that the hottest heating medium temperature will come into contact with the wetter and cooler input biomass feedstock. To avoid the risk of fire, it is necessary to maintain the flue gas inlet temperature below 250 ^{o}C [18]. Additionally, to prevent pre-pyrolysis or material deterioration, the biomass temperature should be kept below 100 ^{o}C [18]. Based on figure 6, the temperature of the dry biomass product output from the rotary dryer based on the simulation is always maintained below 60 ^{o}C, so it is far below the maximum threshold of 100 ^{o}C.

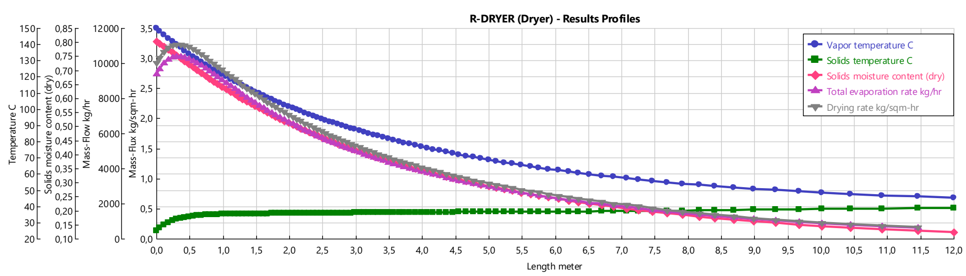

Figure 6. Simulation result's profile.

2.5. Financial Feasibility

2.5.1.Revenue

Compared to the biomass that enters the dryer, the dried biomass produced has a significantly lower moisture content. The Gaur & Reed formula can be used to convert the moisture value of biomass into the LHV calorific value. The Gaur & Reeds correlation as shown in Eq. (4) is frequently used to determine the higher heating value (HHV) by utilizing the ultimate analysis.

$$HHV\left(\frac{MJ}{Kg}\right) = 0{,}35C + 1{,}18H + 0{,}10S - 0{,}10O - 0{,}02N - 0{,}02Ash \quad (4)$$

HHV (gross heating value) is the heating value at which water is condensed from combustion, so the latent heat to evaporate the water is also considered. LHV (net heating value) is the calorific value where the water resulting from combustion remains in the form of steam so that latent heat is not included in the calculation[19]. The formula for obtaining LHV from HHV is shown in Eq. (5) follows.

$$LHV\left(\frac{MJ}{Kg}\right) = HHV\,(1 - M) - 2.447M \quad (5)$$

Once the LHV calorific value is obtained, it is subsequently transformed into converted in energy that can be calculated by using Eq. (6).

$$Energy\ Gen. = \frac{\dot{m}_{biom}\ x\ (\Delta LHV\ x\ \eta_{Syst})\ x\ 4.184}{3600}\ x\ (CF\ x\ 8760)\ x\ HPP \quad (6)$$

Energy generated (USD/year) is obtained by the annual increase in energy production due to a reduction in the moisture content of biomass; ṁbiom (Kg/hour) is the biomass flow rate assumed to be continuous for 24 hours during plant operation; CF represents the plant's capacity factor for a year, which is assumed to be 79%; The constant 4.184 represents the conversion factor from kilocalories (Kcal) to kilojoules (KJ); 3600 seconds for 1 hour; and HPP is the cost of electricity production taken from the average annual tariff of 5.63 cents USD/KWh. Furthermore, revenue is obtained by adding together the amount of energy generated and the salvage value.

2.5.2. Expenses

Within the context of power plant business operations, the components A, B, C, and D are recognized as integral factors in the calculation of the cost of electricity production (HPP). This research will utilize This research will utilize those components to establish the annual cash flow, which is useful for the resulting five investment assessment criteria. Component A refers to the overall financial obligations associated with an investment, encompassing expenses from the initial construction phase to annual depreciation. In this study, the initial investment costs at zero year refer to all the expenses necessary for acquiring the drying system, from its procurement to the completion of construction totalling USD 804,558.02. From the first year to the tenth year, the amount to be paid consists of a principal instalment charge and interest of 10%. This calculation assumes that 70% of the funding is obtained from loans. Component B includes fixed expenses related to the maintenance and operation of the dryer system. These costs remain constant regardless of any changes in dryer production and only appear at labour costs. Component C is a variable component of fuel expenditures. However, due to the utilization of a heating medium from flue gas produced by the boiler, component C is absent in this drying system. Component D also encompasses all expenses associated with operation and maintenance. However, these costs are variable according to the quantity of the product. Component D in this drying system consists of maintenance spare parts and operational costs. One of the largest operational costs is the electricity used by motorized equipment, such as the centrifugal fan motor that is responsible for pushing the flue gas into the rotary dryer. The following Eqs. (7-9) are used to calculate component D.

$$C_{am} = c_{mj}\ x\ (CF\ x\ 8760) \quad (7)$$

$$C_{mh} = \frac{C_m}{M_{sch}} \quad (8)$$

$$C_{ae} = \sum(n_{motor}\ x\ P_{motor})\ x\ (CF\ x\ 8760)\ x\ HPP \quad (9)$$

2.5.3. Investment Assessment Criteria

Investment assessment criteria are standards used to assess the viability, profitability, and overall appeal of a project. They have the ability to evaluate the potential risks and benefits of a project and efficiently distribute resources. Based on the specific attributes and goals of a project, one or more of these factors can be utilized to make a well-informed investment choice. This research will consider five criteria: net present value (NPV), internal rate of return (IRR), payback period (PBP), benefit-cost ratio (B/C), and return on investment (ROI). The calculation of cash flow and the five investment assessment criteria are based on certain assumptions, as shown in Table 6.

Table 6. Some assumptions are used to find cash flow.

Variabel assumptions	Value
Project Life (years)	10
Discount Rate (%)	5.75
Inflation Rate (%)	4.33
Depreciation Rate (%)	6.25
Interest Rate (%)	10
Venture Capital (%)	30
Capacity Factor (%)	79

3. RESULT AND DISCUSSION

3.1. Final Product Dry Biomass

The test results from Aspen simulation indicate that increasing the fuel gas flow and residence time, while decreasing the biomass inlet flow, leads to a reduction in the ultimate moisture content of the dry biomass product. The driest biomass product reached a moisture content of 6.54% when the biomass inlet flow rate was 8 t/h, the fuel gas flow rate was 90 t/h, and the residence period was 25 minutes.

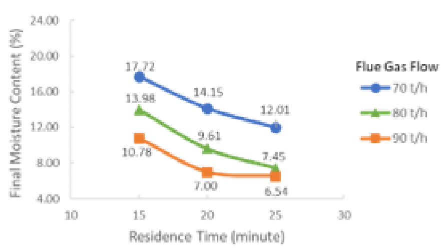

Figure 7. Final moisture at inlet flow biomass 8 t/h.

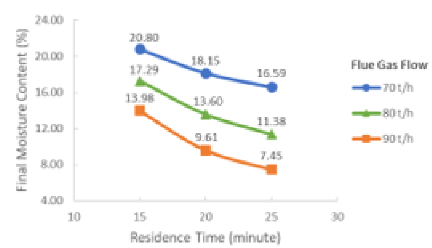

Figure 8. Final moisture at inlet flow biomass 9 t/h.

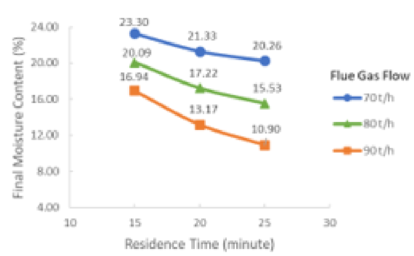

Figure 9. Final moisture at inlet flow biomass 10 t/h.

3.2. Calorific Value and Energy Output

The calorific value (LHV) can be determined by applying formulas (4) and (5). The value is calculated by the moisture content of the end product from the dryer. The disparity in calorific value (ΔLHV) between the pre-drying and the post-drying, represents the obtained benefit difference. The difference is then multiplied by the mass flow rate of the product (ṁbiom) and the efficiency of the CFPP system (ηsyst), producing the actual increase in energy output ΔPout that can be calculated by using Eq. (10).

$$\Delta P_{out}\ (KW) = \frac{\dot{m}_{biom}\ x\ (\Delta LHV\ x\ \eta_{Syst})\ x\ 4.184}{3600} \tag{10}$$

The generator achieved its highest power output of 3949.21 KW when the biomass flow rate was 10 t/h, the flue gas flow rate was 90 t/h, and the residence time was 25 minutes. It is worth noting that despite the end moisture content being 10.90%, which is above the lowest, the maximum power output can be achieved. The final dry biomass flow rate will also decrease as the moisture content value decreases. The flow rate of the end product at that test was 5.64 t/h.

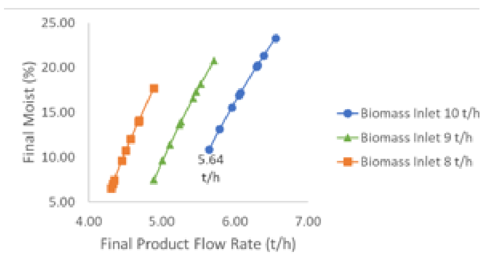

Figure 10. Final moisture vs product flow rate.

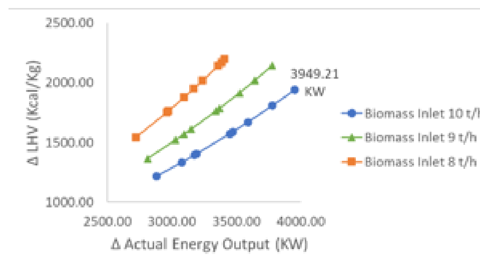

Figure 11. Product LHV vs energy output.

Table 7. Product moisture and energy output from each test.

Biomass Inlet Flow (t/h)	Flue Gas Flow (t/h)	Residence Time (min)	Biomass outlet moisture (%)	Biomass outlet flow (t/h)	Biomass outlet LHV (Kcal/Kg)	Δ Actual Energy Output (KW)	Energi Generated (USD/year)
8	70	15	17.72	4.89	4217.94	2720.29	1,059,885.94
		20	14.15	4.69	4426.30	2958.91	1,152,860.62
		25	12.01	4.57	4551.21	3092.54	1,204,925.42
8	80	15	13.98	4.68	4436.23	2969.63	1,157,037.13
		20	9.61	4.45	4691.29	3235.25	1,260,527.16
		25	7.45	4.35	4817.36	3356.86	1,307,908.00
8	90	15	10.78	4.51	4623.00	3166.48	1,233,732.71
		20	7.00	4.33	4843.63	3381.72	1,317,597.37
		25	6.54	4.30	4870.47	3407.02	1,327,455.22
9	70	15	20.80	5.71	4038.17	2809.02	1,094,460.29
		20	18.15	5.53	4192.84	3026.14	1,179,054.07
		25	16.59	5.43	4283.89	3147.82	1,226,464.83
9	80	15	17.29	5.47	4243.03	3093.73	1,205,389.87
		20	13.60	5.24	4458.41	3368.18	1,312,319.17
		25	11.38	5.11	4587.98	3522.30	1,372,368.73
9	90	15	13.98	5.26	4436.23	3340.86	1,301,676.05
		20	9.61	5.01	4691.29	3639.70	1,418,110.75
		25	7.45	4.89	4817.36	3776.54	1,471,426.59
10	70	15	23.30	6.56	3892.25	2878.10	1,121,375.35
		20	21.33	6.39	4007.23	3071.08	1,196,564.81
		25	20.26	6.31	4069.69	3171.66	1,235,750.72
10	80	15	20.09	6.29	4079.61	3187.41	1,241,889.71
		20	17.22	6.07	4247.12	3443.67	1,341,734.07
		25	15.53	5.95	4345.76	3586.19	1,397,261.67
10	90	15	16.94	6.05	4263.46	3467.64	1,351,073.28
		20	13.17	5.79	4483.50	3775.93	1,471,188.42
		25	10.90	5.64	4616.00	**3949.21**	**1,538,703.67**

3.3. Investment Assessment Criteria

Investment has an inherent connection to the requirement for financial support, which in this scenario is assumed to be obtained through a bank loan. The interest rate is assumed to be 10%, with a repayment duration of 10 years. The venture capital is assumed to constitute 30% of the total cash needed. Component A represents the annual sum of interest and principal repaid on the loan. While the initial investment is only mentioned once at the start of the period, it is essential to consider the salvage value at the conclusion of the period when computing the NPV. The calculation of the salvage value (SV) can be determined by assuming an annual depreciation rate of 6.25% as shiwn in Eq. (11).

$$SV\ (USD) = CF_0 - (CF_0\ x\ Depreciation\ Rate\ x\ Equipment\ Age) \qquad (11)$$

Table 8. Bank loan scheme.

Assumptions	Value
Capital cost (USD)	804,558.02
Venture capital (USD)	241,367.41
Bank loan (USD)	563,190.61
Installment (year)	10
Interest (%)	10

Table 9. Loan repayment cash flow.

Y	Interest	Principal	Total Installment	Remaining Loan
0	-	-	-	563,190.61
1	56,319.06	56,319.06	112,638.12	506,871.55
2	50,687.16	56,319.06	107,006.22	450,552.49
3	45,055.25	56,319.06	101,374.31	394,233.43
4	39,423.34	56,319.06	95,742.40	337,914.37
5	33,791.44	56,319.06	90,110.50	281,595.31
6	28,159.53	56,319.06	84,478.59	225,276.24
7	22,527.62	56,319.06	78,846.69	168,957.18
8	16,895.72	56,319.06	73,214.78	112,638.12
9	11,263.81	56,319.06	67,582.87	56,319.06
10	5,631.91	56,319.06	61,950.97	-

The maximum energy generation of 1,538,703.67 USD/year, as shown in table 7, is obtained when the biomass input is at a rate of 10 t/h, the flue gas flow is at a rate of 90 t/h, and the residence duration is 25 minutes. Table 7 shows that cash flow (USD/year) refers to the decrease in revenue resulting from the deduction of all cost items, components A, B, and D. A trade-off arises when increasing the use of flue gas flow leads to a higher energy output but also requires a great deal of energy to run the motors. The centrifugal fan motor requires a significant quantity of energy to propel exhaust gas from the intake location, IDF outlet #1, to the rotary drier. The energy consumption of a centrifugal fan is approximately ± 10% of the total energy production, as seen in component D.

Table 10. Cash flow and assessment parameter at the highest energy output.

Y	Component (USD)				Expense (USD)	Energy Generated (USD)	Salvage (USD)	Revenue (USD)	Cash Flow (USD)
	A	B	C	D					
0	804,558.02	-	-	-	804,558.02	-	-	-	- 804,558.02
1	112,638.12	17,032.26	-	203,264.42	332,934.80	1,538,703.67	-	1,538,703.67	1,205,768.87
2	107,006.22	17,032.26	-	203,264.42	327,302.89	1,538,703.67	-	1,538,703.67	1,211,400.78
3	101,374.31	17,032.26	-	203,264.42	321,670.99	1,538,703.67	-	1,538,703.67	1,217,032.68
4	95,742.40	17,032.26	-	203,264.42	316,039.08	1,538,703.67	-	1,538,703.67	1,222,664.59
5	90,110.50	17,032.26	-	203,264.42	310,407.17	1,538,703.67	-	1,538,703.67	1,228,296.50
6	84,478.59	17,032.26	-	203,264.42	304,775.27	1,538,703.67	-	1,538,703.67	1,233,928.40
7	78,846.69	17,032.26	-	203,264.42	299,143.36	1,538,703.67	-	1,538,703.67	1,239,560.31
8	73,214.78	17,032.26	-	203,264.42	293,511.46	1,538,703.67	-	1,538,703.67	1,245,192.21
9	67,582.87	17,032.26	-	203,264.42	287,879.55	1,538,703.67	-	1,538,703.67	1,250,824.12
10	61,950.97	17,032.26	-	203,264.42	282,247.64	1,538,703.67	301,709.26	1,840,412.93	1,558,165.28
					3,880,470.23	**15,387,036.69**		**15,688,745.95**	**11,808,275.72**
								NPV (USD)	8,518,085.32
								IRR (%)	150.32
								PBP (year)	0.67
								B/C	4.04
								ROI (%)	304.30

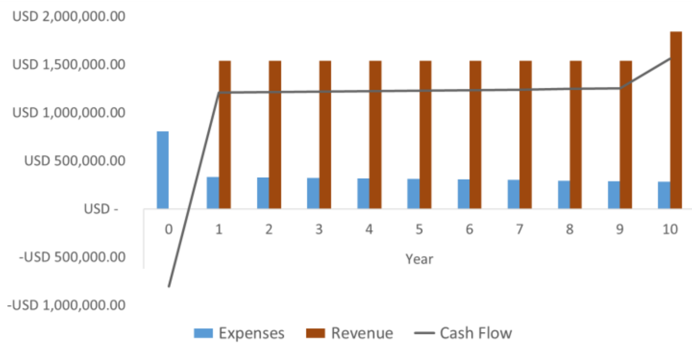

Figure 12. Cash flow trending

During the initial year, there is a deficit in cash flow as a result of capital expenses. Nevertheless, the cash flow has achieved the break-even point within 8 months, or the payback period (PBP) is 0.67 years. A benefit-to-cost (B/C) ratio greater than 1 or 4.04 signifies that this investment is considered worthwhile to proceed with. A positive net present value (NPV) of USD 8,518,085.33 indicates that this investment can provide a profitable return. The internal rate of return (IRR) of 150.32% per year signifies that the incremental average profit level per year resulting from this investment is extremely high. Lastly, the return on investment (ROI) is positive at 304.30%, signifying a substantial proportion of the benefit value acquired from the overall costs over a span of 10 years. Therefore, all parameter indications demonstrate positive values, indicating that this investment has a high potential profit regardless of the moisture product produced because it does not use additional fuel.

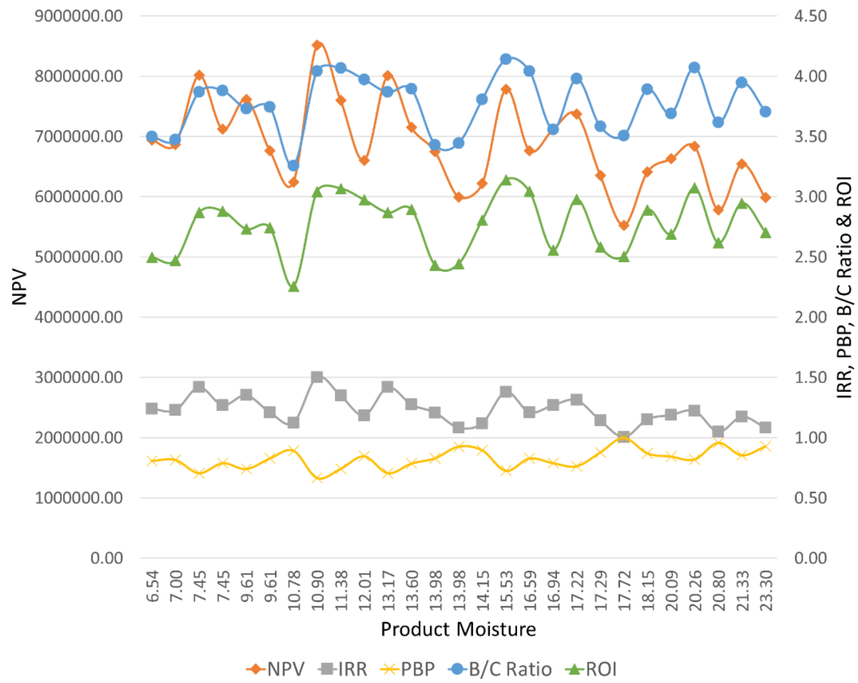

Figure 13. Investment assessment criteria result from each moisture product.

A minor deviation is observed at the highest values of the B/C ratio and ROI, 4.14 and 314.12%, respectively, that occurs at the test point when the biomass inlet flow is 10 t/h, the flue gas flow is 80 t/h, the residence period is 25 minutes, and the final moisture content is 15.53%. This is a result of the trade-off between energy consumption and flue gas volume. By using less energy to push a smaller amount of flue gas, costs are lowered. Nevertheless, this reduction in costs is also accompanied by a decrease in income due to the greater ultimate moisture content.

Table 11. Investment assessment criteria from each test.

Biomass Inlet Flow (t/h)	Flue Gas Flow (t/h)	Residence Time (min)	Biomass Outlet Moisture (%)	NPV (USD)	IRR (%)	PBP (year)	B/C Ratio	ROI (%)
8	70	15	17.72	5,527,610.58	100.59	1.00	3.51	250.79
		20	14.15	6,220,090.96	112.10	0.90	3.81	280.71
		25	12.01	6,607,872.37	118.55	0.85	3.97	297.47
8	80	15	13.98	5,998,363.65	108.42	0.93	3.44	244.43
		20	9.61	6,769,162.91	121.23	0.83	3.74	274.46
		25	7.45	7,122,057.93	127.10	0.79	3.88	288.20
8	90	15	10.78	6,246,645.31	112.54	0.89	3.26	225.71
		20	7.00	6,871,273.75	122.93	0.82	3.47	247.32
		25	6.54	6,944,695.60	124.15	0.81	3.50	249.86
9	70	15	20.80	5,785,122.23	104.87	0.96	3.62	261.92
		20	18.15	6,415,181.19	115.34	0.87	3.89	289.14
		25	16.59	6,768,299.08	121.22	0.83	4.04	304.40
9	80	15	17.29	6,358,497.44	114.40	0.88	3.58	258.46
		20	13.60	7,154,912.58	127.64	0.79	3.89	289.48
		25	11.38	7,602,164.89	135.08	0.74	4.07	306.90
9	90	15	13.98	6,752,690.95	120.96	0.83	3.43	243.22
		20	9.61	7,619,902.85	135.38	0.74	3.73	273.22
		25	7.45	8,017,002.04	141.98	0.71	3.87	286.96
10	70	15	23.30	5,985,586.98	108.20	0.93	3.71	270.58
		20	21.33	6,545,602.11	117.51	0.86	3.95	294.78
		25	20.26	6,837,460.84	122.37	0.82	4.07	307.39
10	80	15	20.09	6,630,350.18	118.92	0.84	3.69	269.05
		20	17.22	7,373,996.32	131.29	0.76	3.98	298.02
		25	15.53	7,787,568.86	138.17	0.73	**4.14**	**314.12**
10	90	15	16.94	7,120,604.17	127.07	0.79	3.56	255.95
		20	13.17	8,015,228.17	141.95	0.71	3.87	286.90
		25	10.90	**8,518,085.33**	**150.32**	**0.67**	4.04	304.30

3.4. Sensitivity Analysis

It is also necessary to pay attention to the influence of changes in five investment assessment criteria on changes in several important aspects that are divided into design aspects and operational aspects. The design aspect consists of an increase in capital costs and a decrease in power output. Meanwhile, operational aspects can be seen in the possibility of a decrease in daily operational duration, an increase in operational costs, and an increase in maintenance costs.

3.4.1. Capital Cost against Investment Assessment Criteria

Capital costs may experience an increase due to unforeseen things, including increases in raw material costs, increases in exchange rates, inflation and so on. The five parameters are in a negative trend if capital costs increase. The payback period, although the graph is increasing, is trending in a negative direction because it takes a longer time to break even on capital returns. The rate of change in PBP is the largest among all criteria, in line with the rate of increase in capital costs. The second major rate of change is occupied by IRR and parabolic as capital costs increase. The greater the change in capital costs, the IRR rate decreases. NPV shows the lowest rate of change of all criteria.

3.4.2. Power Output against Investment Assessment Criteria

During the operational there may be a decrease in energy output, which caused by the margin of error in Aspen Plus calculations, a decrease in the efficiency of the CFPP, a decrease in the calorific value of sawdust due to changes in the type of wood plants obtained, and so on. The five criteria will also experience a negative trend as power output decreases. NPV, IRR and ROI almost coincide with each other which indicates they have the same rate of change. All three of them show a rate of change that is higher than the percentage decrease in energy output. When the energy output drops to –75%, the three parameters even approach -100%. The B/C Ratio shows the rate of change which is the least sensitive. Meanwhile, PBP shows the highest sensitivity. The PBP curve is parabolic, showing an increasingly larger difference as energy output decreases. When the energy output drops to -75%, the Payback Period becomes longer, up to 700% of the PBP when the energy output is without a decrease.

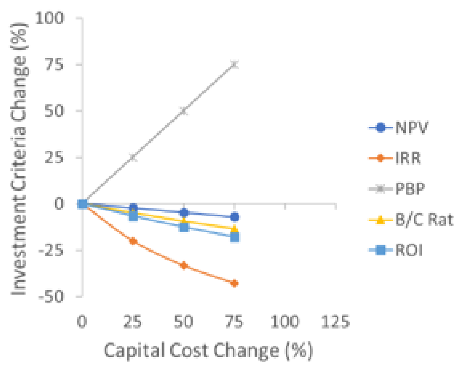

Figure 14. Capital cost.

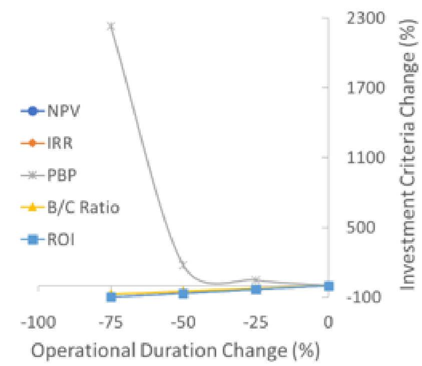

Figure 15. Power output.

3.4.3. Operational Duration against Investment Assessment Criteria

Daily operational duration may vary under the conditions. There were times when the biomass supply was so minimal or may also be due to unplanned equipment downtime. Therefore, it is necessary to pay attention to the impact of reducing the daily operating hours of the drying system on the 5 investment assessment criteria. Almost the same event occurs here when compared with the power output sensitivity analysis. Operational duration is one of the variables in determining the power output value, the values are directly proportional to each other. If the operational duration decreases, the power output will also decrease, likewise if it increases. Thus, the sensitivity of the analysis experiences conditions similar with the power output.

3.4.4. Operational Cost against Investment Assessment Criteria

As explained previously, operational costs consist of employee costs and electric consumption for the needs of driving motors. Operational costs are susceptible to changes due to increases in salary standards or changes in the cost of electricity supply (HPP). How these cost changes affect the 5 investment assessment criteria can be seen below. Operational costs are quite large, holding a portion of expenditure costs with a value of ±25% of capital costs. Therefore, changes in these costs can significantly influence investment assessment criteria. ROI is greatly affected by this cost change, followed by B/C Ratio and PBP. NPV and IRR both coincide with each other and have the least influence due to changes in operational costs.

3.4.5. Maintenance Cost against Investment Assessment Criteria

Maintenance costs consist of time-based maintenance material components, namely lubricants, grease, conveyor belts and bearings. The increase in maintenance costs is likely to be influenced by inflation or changes in exchange rates. The impact on changes to the 5 investment assessment criteria is as follows. It appears that there is a very small influence on investment criteria, because maintenance costs only play a role of ±0.3% of capital costs. The impact on ROI is most felt due to changes in costs, followed by the B/C Ratio. NPV and IRR are again in almost the same condition or close to each other. Meanwhile, PBP also continues to show worsening changes.

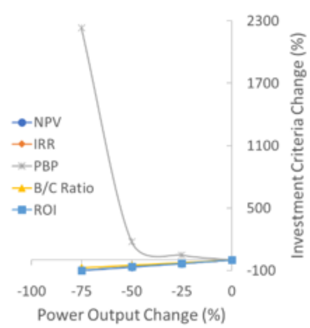

Figure 16. Operational duration.

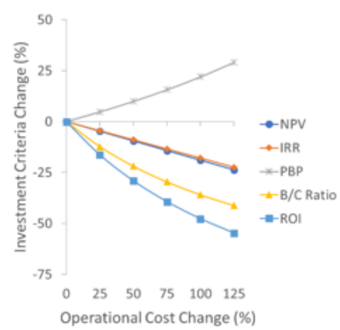

Figure 17. Operational cost.

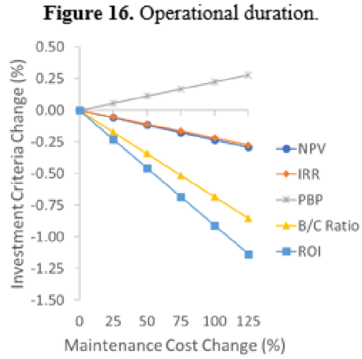

Figure 18. Maintenance cost.

4. CONCLUSION

Typically, all costs involved will increase as the desired moisture level of the product decreases. Contrary to expectations, the lowest-moisture product design does not yield the best profit. This is because there are trade-offs at the flow rate of dry biomass products and the operational and maintenance expenditures. As the moisture content decreases, the ultimate product flow rate decreases proportionally. Similarly, as the moisture content decreases, the amount of electricity required to push the flue gas increases due to the distance away from the pick-up location at IDF #1. The test results indicated that the driest biomass product had a moisture content of 6.54% in the test with an 8 t/h biomass intake, 90 t/h flue gas flow, and a residence time of 25 minutes. Nevertheless, the investment appraisal criteria at this test point did not demonstrate the highest value. The test results showed that the highest values of the three investment criteria were obtained at the biomass inlet flow of 10 t/h, the flue gas flow of 90 t/h, the residence time of 25 minutes, and the moisture content of the biomass product of 10.90%. The corresponding values were USD 8,518,085.33 for NPV, 150.32% for IRR, and 0.67 years for PBP. Meanwhile, the B/C ratio and ROI values, respectively 4.14 and 314.12%, were obtained at the biomass inlet flow of 10 t/h, the flue gas flow of 80 t/h, the residence time of 25 minutes, and the moisture content of the biomass product of 15.53%. The five investment assessment variables show a positive outlook for investors, suggesting that implementing this strategy has the potential to be highly profitable.

Sensitivity analysis on the design aspect shows that an increase in capital costs has a lower impact than a decrease in energy output. On the operational side, the decrease in daily operational time has the most substantial impact on the five investment evaluation criteria, followed by operational costs and maintenance costs. Therefore, it is imperative to reduce elements that can result in a decline in energy output and operational duration.

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