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EVALUATING FINANCIAL VIABILITY OF BOILERS IN PALM OIL MILLS UNDER PROCESSING CAPACITY VARIABILITY: A CASE STUDY APPROACH

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Abstract. *Purpose* – This study evaluates the financial feasibility of boiler investments in palm oil mills, examining the variability in processing capacities resulting from seasonal yields and operational constraints.

Research methodology – A case study was conducted at a palm oil mill in Indonesia, assessing five investment scenarios through sensitivity analysis to compare repair and new boiler strategies at capacities of 48, 51, and 58 tons of FFB per hour. Financial metrics including Net Present Value (NPV), Internal Rate of Return (IRR), and payback period were employed.

Findings – Results exhibit that repairing the boiler, specifically at a capacity of 58 tons/hour, provides the greatest financial returns, with a Net Present Value (NPV) of USD 9.5 million and an Internal Rate of Return (IRR) of 21%, surpassing investments in new boilers. Scenario 5 demonstrated the highest financial resilience in response to variations in costs and revenues.

Research limitations – This research is based on financial assumptions and a singular case study context. Wider generalizations necessitate analysis across various operational contexts.

Practical implications – The findings provide decision-making tools for palm oil mills to optimize capital expenditure in relation to capacity variability and cost efficiency.

Originality/Value – This research incorporates operational variability into financial modeling, offering a novel perspective on boiler investment strategies within the palm oil sector.

Keywords: financial feasibility, boiler investment, palm oil mill, processing capacity.

JEL Classification: Q42, L94, M21.

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1. Introduction

The palm oil industry plays a pivotal role in global agricultural production, with a significant economic impact on many countries, especially those in Southeast Asia, where Malaysia and Indonesia are the largest producers (Hadiguna & Tjahjono, 2017). Palm oil mills rely heavily on boilers to supply the steam required for various stages of production, making boiler efficiency and financial feasibility critical components of operational sustainability (Shen et al., 2017). Despite their importance, the financial viability of boilers in these mills remains underexplored, particularly under conditions of fluctuating processing capacities. Variability in capacity can arise due to seasonal crop yields, machinery maintenance schedules, and market-driven production adjustments, all of which influence operational costs and overall efficiency (Iizumi & Kim, 2019; Pushpalatha et al., 2024). This variability can pose significant challenges for maintaining consistent boiler performance, as each fluctuation impacts fuel consumption, operational efficiency, and, ultimately, the financial returns of boiler investments (Abdullah et al., 2012).

Boilers are capital-intensive investments that incur ongoing operational costs related to fuel, maintenance, and labor (Manzoor et al., 2020). Given the high initial costs and variable expenses, a detailed financial assessment is necessary to guide investment decisions in boilers (Delapedra-Silva et al., 2022). Such an evaluation is especially relevant in settings with capacity fluctuations, as traditional financial models often assume constant capacity, potentially leading to inaccurate financial projections (Nur Chairat et al., 2021). Studies have shown that overlooking variability in processing capacity can result in significant deviations in projected financial outcomes, underscoring the need for assessment frameworks that consider these operational dynamics. Addressing this gap, this study aims to examine the financial viability of boilers under conditions of processing capacity variability, providing insights that align more closely with the operational realities of palm oil mills.

The current state of research has primarily focused on the engineering aspects of boiler efficiency and fuel consumption in palm oil mills, with relatively less emphasis on the financial implications of these factors under varying production capacities (Aziz et al., 2015; Foong et al., 2019). Boiler efficiency research has traditionally aimed to improve energy utilization, reduce emissions, and enhance the overall operational performance of the mill (Rusdi et al., 2022). For example, studies have investigated different types of biomass fuels, such as palm kernel shells (Rusdi et al., 2022) and empty fruit bunches (Brunerová et al., 2018), which are by products of the milling process and can reduce dependence on fossil fuels. While such research is critical for sustainable operations, the economic perspective, particularly how fluctuating capacity affects financial outcomes, remains underexplored.

Operational variability in palm oil mills can be significant due to several factors. Seasonal variations in palm fruit harvests lead to inconsistent feedstock availability, impacting how frequently and efficiently boilers can operate (Panjapornpon et al., 2024). Additionally, routine maintenance schedules, unexpected downtimes, and market-driven shifts in production capacity add layers of complexity to the mill's operational profile (Chiew et al., 2017). When production levels are inconsistent, boilers often do not run at their optimum capacity, which can reduce their fuel efficiency and increase per-unit operational costs (Bennett & Elwell, 2020). These changes in boiler performance can significantly affect long-term economic projections, yet traditional financial assessments for boiler investments often assume a stable or near-constant processing capacity, thus potentially overlooking these cost variations (Manzoor et al., 2020).

To address this gap, there is a need for a more nuanced financial assessment model that incorporates capacity variability as a core factor. A financial model that accounts for capacity variability can provide a more realistic view of Net Present Value (NPV), Internal Rate of Return (IRR), and other financial metrics by simulating the effects of fluctuating capacity on revenue and costs. For instance, sensitivity analysis which is a method that adjusts one or more variables to observe changes in financial outcomes, could be applied to study the impact of high and low production scenarios on financial viability. By using a model that integrates both operational and financial variability, stakeholders can better understand the economic risks and benefits associated with boiler investments, ultimately making more informed decisions (Chakrabarty & Nag, 2023; Li et al., 2018).

This study hypothesizes that processing capacity variability significantly affects the financial feasibility of boilers in palm oil mills. Specifically, it is anticipated that varying capacities will impact both capital recovery timelines and overall financial returns, potentially challenging traditional investment decisions based on static capacity assumptions. The findings are expected to offer valuable insights for stakeholders in the palm oil industry, providing a robust framework for evaluating boiler investments under variable operating conditions.

2. Literature review

The economic viability of boiler investments in the palm oil sector has gained prominence in recent years, particularly in the context of Southeast Asia. This region, led by Indonesia and Malaysia, is a global hub for palm oil production, where steam-driven processes are vital to oil extraction. In such energy-intensive environments, the decision to invest in new boilers or to repair and upgrade existing units requires a careful balance between financial sustainability and operational efficiency.

A growing body of research emphasizes the importance of applying comprehensive financial metrics, such as NPV, IRR, and payback period, to evaluate investment decisions in energy infrastructure. These indicators have proven useful in biomass-based and renewable energy projects, particularly when aligned with uncertainty modeling and scenario analysis techniques (Delapedra-Silva et al., 2022).

Cost-effective boiler operation has been shown to be achievable through the utilization of internal biomass waste streams, including Empty Fruit Bunches (EFB), mesocarp fibers, and palm kernel shells. These biomass sources not only provide thermal energy but also contribute to cost savings by reducing reliance on external fuels (Liew et al., 2016). Studies examining bio-oil production from palm oil waste have also highlighted its potential to enhance financial returns and reduce the environmental footprint of milling operations (Buana et al., 2023).

Rather than relying solely on capital-intensive new installations, several analyses have shown that retrofitting and maintaining existing boiler units can offer superior financial outcomes under specific capacity utilization scenarios. When operational and maintenance costs are tightly managed, repaired boiler systems have demonstrated favorable NPV and IRR outcomes, particularly in mid- to high-capacity operating environments (Manzoor et al., 2020).

It has been observed that financial models that fail to incorporate capacity variability often underestimate risk. Incorporating stochastic variables such as fluctuating fruit yields, inconsistent throughput, and fuel price volatility into the financial assessment improves the accuracy of projected investment returns. Such modeling techniques provide clearer thresholds for economic feasibility and help identify scenarios under which investments may fail to recover their capital (Ghavidast & Khakzar Bafruei, 2024).

From a financial perspective, systems that utilize biomass-based fuels tend to reach break-even points faster than conventional systems. In one example, a Sumatra-based mill equipped with a biogas power plant achieved capital payback within five years, largely due to the use of internal fuel resources and avoided energy procurement costs (Dewi, 2020). Similar benefits have been documented in Malaysia, where biogas systems that repurpose organic waste reduced capital risks and improved investment resilience (Abas et al., 2013).

Optimization of boiler performance is not limited to technical upgrades alone; integration of energy recovery systems and process redesigns has been shown to reduce operating expenses by as much as 20% (Aziz et al., 2015). Meanwhile, hybrid financial and process optimization models developed for palm oil mills suggest that maximizing thermal efficiency directly contributes to improved investment returns (Foong et al., 2019). As part of a broader strategy to enhance investment robustness, adaptive systems that respond to external variables such as climate shifts and energy market dynamics have been increasingly proposed. Application of reinforcement learning and AI-based control frameworks in energy management for palm oil mills has demonstrated greater NPV stability under fluctuating environmental and operational conditions (Panjapornpon et al., 2024).

Attention has also been drawn to the importance of considering long-term financial risks, particularly those stemming from climate and regulatory uncertainties. Integrating risk modeling into financial planning supports the identification of cost-effective and resilient investment pathways, especially for industries heavily reliant on energy systems (Chakrabarty & Nag, 2023). Enhancing financial performance in boiler systems also depends on effective monitoring and predictive maintenance. Data-driven approaches, such as real-time monitoring of boiler water quality and predictive fault detection, have shown to reduce maintenance costs and prolong equipment life (Rusdi et al., 2022). These operational improvements indirectly reinforce investment outcomes by reducing unexpected downtime and repair expenses.

The application of exergoeconomic analysis has revealed that thermal integration strategies in palm oil biorefineries contribute to enhanced energy use and faster payback times. Economic-environmental models combining capital and environmental metrics can guide decision-makers toward sustainable and profitable energy system configurations (Julio et al., 2021). Fuel preparation and quality control also influence the financial performance of biomass-fueled boilers. Pelletizing EFB waste, for instance, has been shown to improve combustion efficiency and fuel consistency, enabling better alignment between energy supply and demand (Brunerová et al., 2018). Moreover, lifecycle cost assessment tools such as NPV continue to serve as standard evaluative frameworks in capital project analysis. Their widespread application across infrastructure sectors underscores their utility in tracking capital recovery, comparing alternative investment options, and ensuring financial sustainability over long planning horizons (Shou, 2022). The use of integrated process-energy-finance optimization models further strengthens the economic rationale for repair strategies. When existing boilers are strategically maintained and fuel supply is managed internally, mills often achieve better financial outcomes compared to full-scale replacement strategies, particularly in high-throughput scenarios (Delapedra-Silva et al., 2022; Foong et al., 2019).

Finally, research on financial feasibility within the palm oil sector has expanded significantly, particularly focusing on energy infrastructure such as biomass-based boiler systems. Early studies primarily emphasized engineering performance, including boiler efficiency, emissions reduction, and fuel flexibility. As the industry matured, attention shifted toward techno-economic assessments that quantify the financial return of boiler installations. More recent literature incorporates dynamic modeling approaches that account for operational variability, such as processing capacity fluctuations and fuel cost volatility, to improve the robustness of investment decisions. Despite these advancements, a consistent gap remains in addressing how sensitivity-informed financial models can guide boiler investment strategies under variable capacity scenarios in Southeast Asian palm oil mills. This study builds upon these developments by integrating dynamic financial evaluation with operational realities, aiming to offer a more resilient investment framework tailored to the region's unique industrial conditions.

3. Financial data and methods

To provide a clear overview of the research process, a methodology flowchart for the current study, as illustrated in Figure 1, has been developed and divided into three main stages, to outline each step involved in assessing the financial feasibility of a new boiler investment under variable processing capacities in a palm oil mill.

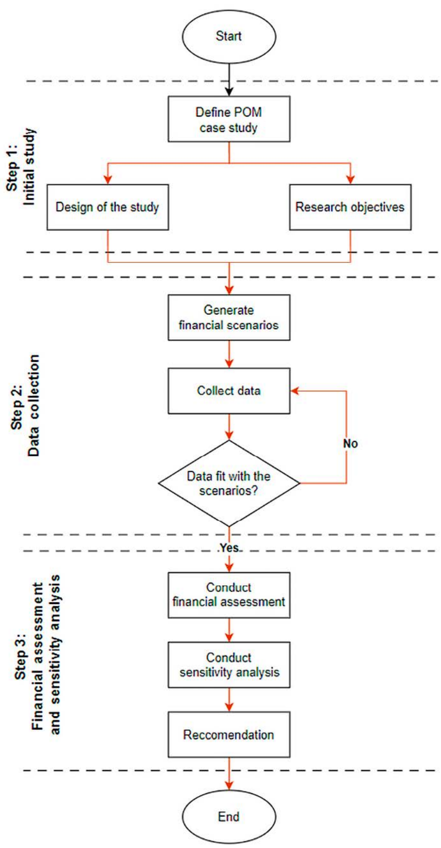

Figure 1. Methodology for financial feasibility assessment of boiler investment in a palm oil mill

The process begins with defining the specific case study of the Palm Oil Mill (POM), including a detailed description of its operational conditions, specifically the challenges and objectives related to boiler capacity and performance. This stage is divided into two key components: the design of the study and the establishment of research objectives. The study design outlines the framework and approach for investigating boiler feasibility, while the research objectives clarify the specific goals, focusing on the operational and financial analysis of a new boiler within the mill's current setting.

In the second stage, financial scenarios are generated based on different levels of boiler capacity utilization, capturing a range of possible operational conditions that might impact the financial performance of the boiler. Following scenario generation, data collection is undertaken to gather relevant operational and financial information that aligns with these scenarios. After collecting the data, a validation step checks whether the data aligns with the defined scenarios. If the data do not match the requirements of the scenarios, additional data may need to be collected, iterating this step as necessary. Once the data are confirmed to fit the scenarios, the process moves forward to the financial assessment phase.

In the final stage, a financial assessment is conducted, where key financial metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR) are calculated based on the collected data. A sensitivity analysis is then performed to assess how variations in critical factors, like production capacity, fuel costs, and maintenance expenses, influence the financial outcomes (Ebazadeh et al., 2024). This step helps to determine the robustness of the investment under different operational scenarios. Finally, based on the results of the financial assessment and sensitivity analysis, recommendations are formulated to provide stakeholders with informed guidance regarding the feasibility of investing in a new boiler.

3.1. Study design

This study was conducted as a case analysis within a palm oil mill in Kalimantan Island, Indonesia, that operates with two boiler units, of which only one remains functional to meet the mill's steam requirements. Boiler 1, with a steam production capacity of 20 tons per hour, was decommissioned due to damage to its water pipes and superheater, rendering it inoperable. Consequently, Boiler 2, with a capacity of 30 tons of steam per hour, now functions as the sole active unit responsible for fulfilling the mill's steam needs. This reliance on a single boiler introduces significant challenges in maintaining operational stability, especially when production demands fluctuate. Given these circumstances, the mill is exploring the feasibility of acquiring a new boiler, with this decision being informed by a rigorous financial analysis of the potential investment (Julio et al., 2021).

3.2. Financial assessment scenarios

The financial assessment scenarios of this study explore the feasibility of investing in new boilers versus repairing existing ones at the POM facility. To provide a comprehensive evaluation, Table 1 summarizes multiple scenarios were analyzed based on distinct processing capacities – 48, 51, and 58 tons of FFB per hour – allowing for a detailed examination of how different operational levels impact financial viability.

Table 1. Financial assessment scenario

Description	Scenario				
	1	2	3	4	5
Processing capacity (tons FFB per hour)	48	48	51	51	58
Repair	No	Yes	No	No	Yes
Invest new boiler	Yes	No	No	Yes	Yes

In Scenario 1, the processing capacity is set at 48 tons of FFB per hour, with no repair or new investment considered. This scenario represents the base condition where the mill operates under current constraints without any changes to the boiler system. Scenario 2 maintains the same processing capacity (48 tons per hour) but includes repair costs, reflecting a situation where minimal investment is made to restore partial functionality to the existing boiler. Scenario 3 examines a slight increase in processing capacity to 51 tons per hour without repairing or investing in a new boiler. This scenario helps assess the potential impact of higher processing demand on the existing boiler without additional investment. Scenario 4 also operates at 51 tons per hour but includes repair costs, allowing for a comparison between operating the boiler as-is and with necessary repairs at a mid-level capacity. Finally, Scenario 5 represents the highest processing capacity analyzed, at 58 tons of FFB per hour, without any repair or new boiler investment. This scenario tests the feasibility of operating at an elevated capacity without maintenance, helping to identify whether the existing boiler can sustain higher demand without significant efficiency or financial drawbacks.

3.3. Data and assumption

The financial feasibility assessment of the boiler investment and repairing at the mill facility is based on a range of operational and financial assumptions, presented in Tables 2–3. The financial data in Table 2 provides essential parameters for calculating the project's cost structure and financial viability. A loan covering 75% of the investment cost is assumed, with a 10-year repayment term at an annual interest rate of 13%. Other costs, such as wages, operating expenses, and maintenance, are set to escalate yearly, with wages increasing by 3% annually from the second year onward, operational costs by 6%, and maintenance costs by 3%. Insurance and depreciation costs are both fixed at 0.5% of the total investment cost per year, with zero residual value at the end of the investment. Additional general expenses increase at a rate of 4% per year from the second year onward. An income tax rate of 25% is applied to the gross profit, ensuring accurate post-tax financial projections.

Table 2. Cost and financial data

Parameter	Unit	Value
Loan for investment	%	70
Loan interest	%	13.5
Duration	Years	10
O&M	%	20
Insurance	%	0.8
Depreciation	%	0.5
Income tax	%	20

Table 3 outlines the operational data, including key parameters such as oil yield from Fresh Fruit Bunches (FFB), which is estimated at 20% of FFB, and the contribution of Crude Palm Oil (CPO) sales, which accounts for 67% of the total oil yield. The price assumptions are set to remain constant throughout the investment period, with CPO and shell prices set at USD 369 per ton and USD 33 per ton, respectively. Additionally, the cofiring burner cost is fixed at USD 66,667 per unit, while the facility operates approximately 5,500 hours annually, based on the production plan. Pre-investment capacity is set at 40 tons of FFB per hour, which will increase to 60 tons per hour post-investment, reflecting the upgraded capacity.

The NPV Equation is used to calculate the present value of future cash flows associated with the investment (Ghavidast & Khakzar Bafruei, 2024). NPV provides a snapshot of the expected profitability by discounting future cash inflows and outflows back to their present value, allowing decision-makers to assess whether the investment will yield a positive financial return (Shou, 2022). The NPV Equation is expressed as:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{\left(1+r\right)^t} - C_0 \,. \tag{1}$$

In this equation, R_t represents the net cash inflow during each period t, r is the discount rate (reflecting the time value of money), and C_0 is the initial cost of the investment. Calculating NPV involves summing the discounted cash inflows for each time period and subtracting the initial investment. A positive NPV suggests that the project will generate more cash than it costs, indicating it is financially viable, while a negative NPV indicates the investment may not be profitable.

Table 3. Main operational and economic parameters

Parameter	Unit	Value
Oil yield	%	20
CPO price	USD	369
Processing hours	Hours per year	5,500
Processing capacity	Tons of FFB per hour	40

The IRR, on the other hand, represents the discount rate at which the NPV of the investment's cash flows becomes zero. In other words, IRR is the expected annualized return on the investment. It is particularly useful for comparing the profitability of different investment options, as a higher IRR typically indicates a more attractive investment. If the IRR of the project exceeds the required rate of return or the company's cost of capital, the investment can be considered favorable. The IRR is calculated by setting the NPV Equation to zero and solving for the discount rate, r:

$$0 = \sum_{t=0}^{n} \frac{R_t}{\left(1+IRR\right)^t} - C_0 . \tag{2}$$

Additionally, the payback period measures how quickly the initial investment can be recovered from the project's cash inflows. It provides insight into the risk associated with the investment, with a shorter payback period generally indicating a lower risk. In cases where cash inflows vary year to year, the payback period is determined by summing annual cash inflows until they equal the initial investment. For projects with consistent annual cash inflows, the payback period is calculated using the Equation:

$$Payback\,Period = \frac{C_0}{Annual\ cash\ inflow}. \tag{3}$$

Finally, sensitivity analysis was performed to evaluate the impact of fluctuating processing capacities on financial outcomes. This approach involved varying one parameter at a time (e.g., processing capacity, fuel cost) while holding others constant to isolate each factor's effect on NPV, IRR, and payback period.

4. Results

4.1. Financial analysis and investment strategy evaluation

The following Table 4 presents financial outcomes across five different scenarios for evaluating boiler investments in a palm oil mill. Each scenario has different configurations of investment, including whether to invest in a new boiler, repair existing boiler, and purchase additional equipment.

The financial analysis highlights a clear preference for repairing existing boilers over purchasing new ones across different processing capacities. Repairing options yield higher NPVs and IRRs, indicating stronger returns on investment. For instance, Scenario 5, which maximizes processing capacity at 58 tons per hour through boiler repair, generates the highest NPV of 9.5 million USD and an impressive IRR of 21%. This scenario also has the shortest payback period of only 3 years, underscoring its efficiency in generating cash flow quickly. In contrast, the scenarios that involve purchasing new boilers (such as Scenarios 1 and 4) require significantly higher initial investments and lead to longer payback periods of 5 years, along with lower NPVs and IRRs. These findings suggest that unless a new boiler is essential for operational reasons, repairing provides a more economically sound approach by balancing lower capital outlay with high profitability.

Capacity expansion emerges as a key driver of financial performance in this analysis. The scenarios operating at 51 and 58 tons per hour produce significantly higher NPVs and IRRs than those operating at 48 tons, reflecting the positive impact of increased throughput on revenue generation. Scenario 5, which combines a 58-ton capacity with repairing, optimally leverages this effect by delivering the highest profitability with a relatively low investment cost. Even within lower capacities, the benefits of repairing over new investment remain evident. For instance, at 48 tons, Scenario 2 (which focuses on repair) surpasses Scenario 1 (new boiler investment) with a higher NPV of 6.7 million USD and a stronger IRR of 18%, reinforcing the financial advantage of repairing over new capital expenditure across all capacity levels.

From a risk management perspective, scenarios involving boiler repairs offer the added benefit of faster capital recovery. Shorter payback periods improve cash flow stability and reduce the risk of prolonged financial exposure, which is particularly valuable for facilities aiming to minimize financial risk. With lower initial investments and rapid payback, repair-based

Table 4. Financial assessment scenario

Description	Scenario				
	1	2	3	4	5
Processing capacity (tons FFB per hour)	48	48	51	51	58
Repair	No	Yes	Yes	No	Yes
Invest new boiler	Yes	No	No	Yes	No
Total investment (million USD)	1.7	0.6	1.02	1.7	1.02
Total O&M cost (million USD)	0.34	0.12	0.2	0.34	0.2
Total revenue (million USD)	36.4	36.4	38.6	38.6	43
NPV (million USD)	5.2	6.7	8.3	5.6	9.5
IRR (%)	14	18	19	15	21
Payback period (years)	5	4	4	5	3

scenarios free up capital sooner, enabling palm oil mill to reinvest in other operational areas or respond flexibly to changing market conditions. On the other hand, the higher capital commitment and slower returns associated with new boiler investments may be less attractive without specific operational needs, such as increased reliability or enhanced efficiency that justifies the extra cost.

Consequently, the analysis strongly favors repairing strategies, particularly Scenario 5, as the optimal choice for the mill. This approach aligns with the facility's financial objectives by maximizing return on investment while maintaining flexibility and reducing financial risk. Repairing at 58 tons per hour allows palm oil mill to achieve enhanced profitability without the burden of excessive capital expenditure, thus balancing growth and financial stability. This strategy enables the facility to respond to future capacity demands, maintain a healthy cash flow, and leverage existing assets effectively, making it the most prudent investment choice.

4.2. Sensitivity analysis

The sensitivity analysis examines how changes in investment cost, revenue, O&M cost, and discount rate impact each scenario's NPV, IRR, and payback period. Scenarios 1 and 4 (new boilers) show high sensitivity to cost and revenue changes, with reduced NPV and IRR under increased costs or lower revenue. In contrast, repair scenarios (2, 3, and 5), especially Scenario 5, maintain stability due to lower initial costs and better resilience to revenue decreases. Increased O&M costs moderately affect all, but repair scenarios benefit more from cost stability. Lower discount rates improve NPV for all scenarios, while higher rates reduce NPV and impact new boiler investments most. Scenario 5 stands out as the most robust across all conditions.

Figure 2 illustrates NPV sensitivity across five scenarios. Scenario 5 consistently shows the highest NPV across all conditions, affirming it as the most financially robust option due to its high capacity (58 tons FFB per hour) and resilience to cost increases and revenue fluctuations. Increasing investment costs by 10% impacts Scenarios 1 and 4 the most, as these involve new boiler investments, while reducing costs by 10% enhances NPV for all scenarios but keeps Scenario 5 in the lead. A 10% revenue increase benefits all, especially Scenario 5, which reaches an NPV of 10.5 million USD, underscoring its potential to capitalize on favorable market conditions. Conversely, a 10% revenue drop has the largest negative effect on new boiler investments (Scenarios 1 and 4), reinforcing the advantage of repair-based options like Scenario 5. Overall, this analysis supports Scenario 5 as the optimal choice, balancing high profitability with minimal financial risk.

The IRR sensitivity analysis illustrates the relative robustness of each scenario under changes in investment costs and revenue as shown in Figure 3. In the base case, Scenario 5 (repairing at 58 tons FFB per hour) achieves the highest IRR, reflecting its strong profitability and efficient capital use. When investment costs increase by 10%, IRR decreases across all scenarios, with the most pronounced impact on Scenarios 1 and 4, which involve new boiler investments. This indicates that new boiler options are more sensitive to capital cost

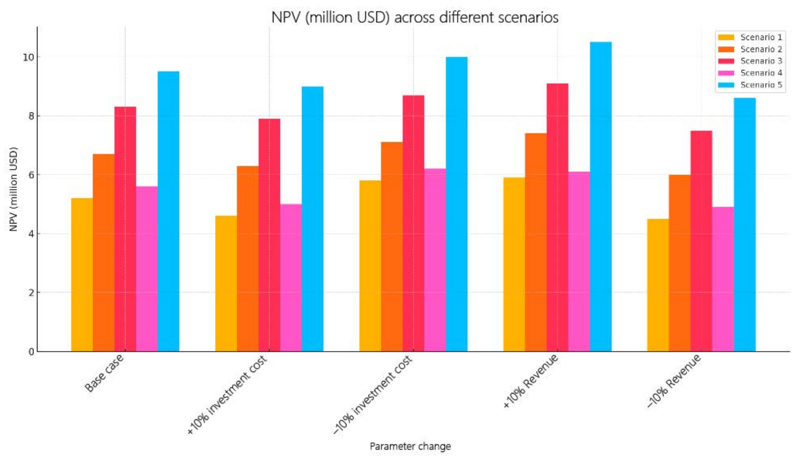

Figure 2. Impact of investment cost and revenue changes on NPV across boiler investment scenarios

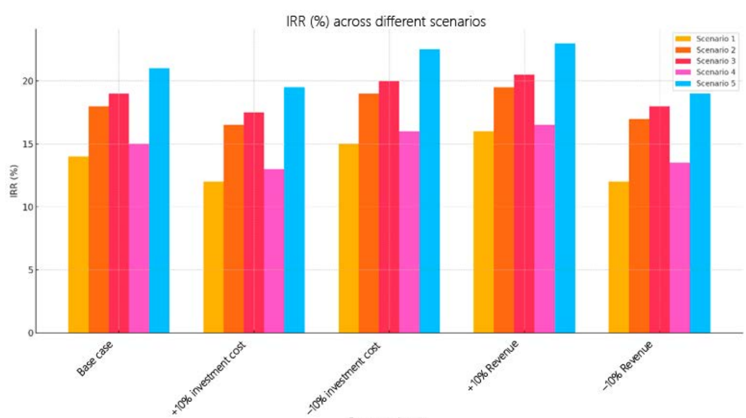

Figure 3. Impact of investment cost and revenue changes on IRR across boiler investment scenarios

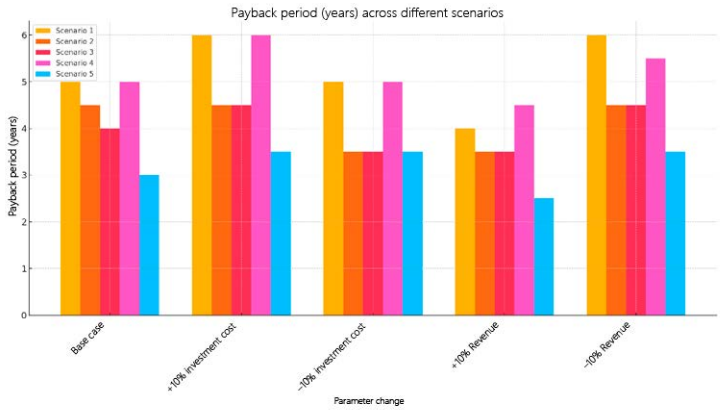

Figure 4. Impact of investment cost and revenue changes on payback period across boiler investment scenarios

fluctuations, whereas repairing scenarios, especially Scenario 5, remain resilient. A 10% decrease in investment costs enhances the IRR for all, with Scenario 5 reaching over 22%, highlighting its financial advantage. Revenue changes have an even greater effect; a 10% increase in revenue boosts IRR substantially across all scenarios, with Scenario 5 again benefiting the most, reaching an IRR above 23%. However, a 10% revenue reduction has a notable negative impact, particularly for Scenarios 1 and 4, which see their IRRs fall closer to the threshold for viability. This analysis confirms that repair-focused options, especially Scenario 5, are better equipped to withstand both cost increases and revenue fluctuations, making them the most robust and financially stable choices.

Moreover, the payback period analysis reveals that Scenario 5 consistently has the shortest payback time across all conditions, as illustrated in Figure 4, highlighting its rapid capital recovery. A 10% increase in investment cost slightly lengthens the payback period for all scenarios, with the most impact on Scenarios 1 and 4, which rely on new boiler investments. Conversely, a 10% reduction in investment cost shortens the payback period for each scenario, with Scenario 5 achieving the lowest duration. Revenue changes have the most significant effect; a 10% increase in revenue notably reduces payback periods across scenarios, especially in Scenario 5, which achieves under three years. However, a 10% revenue decrease lengthens payback periods for all, making Scenarios 1 and 4 the least attractive options due to their extended recovery times. This analysis reinforces Scenario 5's financial strength and efficiency in capital recovery.

5. Discussion

5.1. Comparison with previous studies

The results of this study indicate that the financial feasibility of utilizing palm oil mill waste for boiler investment is highly promising, as reflected in the positive Net Present Value (NPV), high Internal Rate of Return (IRR), and relatively short Payback Period (PP). These findings are consistent with previous studies, such as Abas (2013), who found that waste-to-energy projects in agro-industrial settings demonstrated similar financial viability, particularly when optimized with efficient capital allocation and government incentives. Similarly, Dewi (2020) analyzed the feasibility of biogas power plants in palm oil mills and concluded that such projects could yield positive financial returns under optimal waste management strategies.

In line with Liew et al. (2016), who analyzed the cost-benefit aspects of biomass-based energy investments, this study reaffirms that the economic potential of palm oil mill waste utilization increases when waste availability and processing costs are optimized. Moreover, previous research by Buana et al. (2023) emphasized that energy conversion technologies applied in palm oil mills could achieve a high IRR when combined with strategic operational efficiency measures, such as co-firing with alternative biofuels. The IRR obtained in this study aligns with their findings, suggesting that waste-based boiler investments in the palm oil industry remain financially attractive under favorable economic conditions.

However, this study highlights that financial performance may vary depending on fuel conversion efficiency, technological adoption, and capital investment levels, as also suggested by Liew et al. (2016) in their research on renewable energy infrastructure projects. While their study found that government subsidies and carbon credit incentives significantly improve project feasibility, our findings suggest that even without external incentives, palm oil mills can achieve profitable outcomes by leveraging high biomass availability and efficient operational management.

A key difference between this study and previous research is the sensitivity analysis on fluctuating fuel costs and operational expenditures. Unlike Buana et al. (2023), who assumed fixed cost structures for biomass processing, our study incorporates dynamic pricing scenarios to account for market volatility. This approach provides a more realistic and adaptive financial outlook, ensuring that investment decisions remain robust under uncertain economic conditions.

From an industry perspective, these findings support the argument that integrating waste-based energy solutions in palm oil mills can enhance sustainability while maintaining profitability. This aligns with Dewi (2020), who emphasized that biomass-to-energy transitions contribute to both economic gains and environmental impact reductions. However, this study further contributes by highlighting the importance of strategic investment timing and operational efficiency improvements to maximize financial returns

5.2. Investment strategy recommendations

Based on the sensitivity analysis results indicate that Scenario 5, which involves repairing the boiler at a capacity of 58 tons FFB per hour, is the most financially resilient option. This scenario consistently demonstrates high NPV, IRR, and the shortest payback period across all tested conditions, maintaining strong performance even when investment costs rise or revenue decline. This makes Scenario 5 the preferred choice for achieving both profitability and financial stability. In contrast, Scenarios 1 and 4, which involve new boiler investments, exhibit greater sensitivity to changes in both investment costs and revenue, resulting in lower financial returns and extended payback periods under adverse conditions. New boiler investments should therefore only be considered if operational demands absolutely require them, as repair-focused options generally provide better financial outcomes. Additionally, the analysis reveals that revenue fluctuations have the most significant impact on profitability for all scenarios, highlighting the importance of optimizing revenue through improved production efficiency, secure supply chains, and favorable CPO market conditions. Revenue enhancement efforts are particularly advantageous for Scenario 5, where increased income potential substantially raises profitability and shortens payback periods. Alongside revenue optimization, careful management of both investment and O&M costs is crucial for sustaining profitability. Controlling these expenses will further improve the financial performance of all scenarios, especially in environments of uncertain market conditions. Therefore, Scenario 5, supported by revenue optimization and cost control, emerges as the recommended strategy for balancing high returns and financial resilience in the long term.

6. Conclusions

This study concludes that repairing existing boilers, especially at higher capacities, provides the most financially robust and resilient investment strategy for palm oil mills. Sensitivity analysis shows that repairing options, particularly Scenario 5 at 58 tons FFB per hour, yield the highest NPV, IRR, and shortest payback period, outperforming new boiler investments across varied cost and revenue conditions. Scenarios involving new boiler installations (Scenarios 1 and 4) were found to be significantly more sensitive to cost increases and revenue fluctuations, leading to reduced financial returns and longer recovery times. These results support the hypothesis that repairing, with its lower capital outlay and consistent profitability, is generally a preferable approach to boiler investment in the absence of pressing technological or operational needs for new equipment.

The findings emphasize the importance of revenue optimization through production efficiency and favorable CPO pricing, as well as strict control of investment and operational costs to enhance financial outcomes. While this analysis provides a solid framework for making informed investment decisions, the study has certain limitations, including a reliance on specific financial assumptions and market conditions that may vary over time. Future research could investigate the effects of different market dynamics or technological advancements in boiler systems on investment outcomes, offering broader insights for decision-makers in the palm oil industry. Overall, this study contributes to a deeper understanding of financially effective strategies for boiler investments, potentially guiding future research and practice in optimizing cost and revenue efficiencies within the industry.

Future studies should explore the impact of market fluctuations (CPO prices, fuel costs, and maintenance expenses) on investment feasibility using dynamic financial models. Additionally, technological advancements in boiler efficiency, emission control, and biomass co-firing should be assessed to determine their long-term financial viability. Comparative research across different mill sizes (smallholder vs. industrial) could provide tailored investment strategies. Moreover, the influence of regulatory policies, such as carbon taxes and green energy incentives, should be evaluated for their effect on investment decisions.

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