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Techno-Economic Analysis of Decisions to Upgrade Gas Turbine Blade Models: A Comparative Case Study of the Investment Value of Upgrading The Row 1 Blades of a 130 MW Gas Turbine

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Techno-Economic Analysis; Gas Turbine Efficiency; Investment Value; *Repair*; *Upgrade of* MXL Blades.

Abstract

This study aimed to conduct a techno-economic analysis of the decision to upgrade the Blade 1 component to the MXL type in a gas turbine unit by comparing the investment schemes for Gas Turbine (GT) 21 and GT 13. In 2021, GT 21 required an upgrade to MXL technology because it had reached its end of service life, whereas GT 13 was scheduled for repair because it still had remaining operational life. The methodology involved a comprehensive comparison of the two expenditure schemes over the 2014–2031 period, considering investment costs, repair costs, and operational profit values. Performance test evaluations showed that MXL technology applied to GT 21 increased efficiency by 0.18%. This efficiency improvement contributed to reduced natural gas consumption and increased electricity production, generating a total financial benefit of more than IDR 6 billion during the 2021–2025 period. Despite the potential efficiency improvements, the financial analysis of the GT 13 case showed that the total net cost of the upgrade scheme reached IDR 71,658,492,352.67 after accounting for efficiency gains. This value was higher than the repair scheme, which required a total cost of IDR 66,297,933,022.57. The findings confirm that maintaining the repair scheme for GT 13 was the most financially advantageous decision, as the company avoided additional investment expenditure of IDR 5,360,559,330.10 compared with implementing the upgrade program.

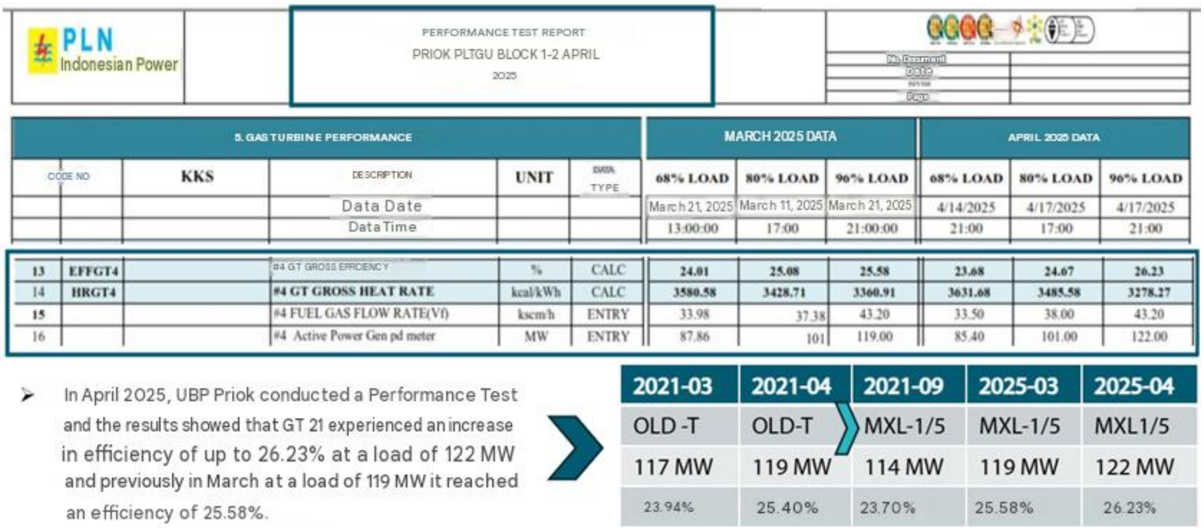
INTRODUCTION

The electricity sector is a backbone of the national economy, requiring high operational reliability and sustainable performance. Gas turbines play a strategic role as fast-response generating units for meeting peak load demands and as key components of combined-cycle power plants. In Indonesia, gas turbine-based power plants, such as combined-cycle power plants (Pembangkit Listrik Tenaga Gas dan Uap/PLTGU), contribute significantly to the national energy mix; therefore, their reliability directly affects electricity supply stability (Islam et al. 2024; Iweh et al. 2021; Rusin et al. 2023). Gas turbine blades are among the most critical components because they operate under extreme temperatures and pressures, resulting in gradual degradation that ultimately limits thermal efficiency and power generation capacity (Boyce, 2011; PT PLN (Persero) Indonesia Power UBP Priok, 2023).

The degradation of gas turbine blade components presents a major challenge for power plant operators, particularly in determining the most technically and financially efficient maintenance strategy. The two primary options available are repair strategies aimed at restoring blade conditions to their original specifications and technology upgrades to newer-generation blade designs that offer improved performance. The selection between these strategies depends not only on component condition but also on remaining service life, investment value, potential efficiency improvements, and long-term operational planning considerations (Barringer, 2003; Saravanamuttoo et al., 2017). Inappropriate decisions may result in significant budget inefficiencies or reduced plant performance, leading to sustained operational losses (Enbar et al. 2015; Settembre-Blundo et al. 2021; Yap et al. 2019).

Techno-economic analysis is a comprehensive and widely applied approach in engineering studies for evaluating investment decisions by simultaneously considering technical performance and financial impacts (Kumar & Sharma, 2018; Roques et al., 2006). Previous studies have applied this approach to evaluate power plant components, including the assessment of gas turbine blade replacement feasibility under various operating conditions (Hakan, 2020; Zwebek & Pilidis, 2003). However, studies specifically comparing upgrade and repair strategies for gas turbine units operating in parallel within the same system, using actual field data as the basis for analysis, remain limited in the existing literature. This condition highlights the need for case study-based research supported by valid and measurable operational data (Shekh 2025; Tarapder 2025).

This study presents a case study of the Priok PLTGU, focusing on two 130 MW gas turbine units, namely Gas Turbine (GT) 21 and GT 13, which had different technical conditions in 2021. In GT 21, the Blade 1 component had reached its end of service life, making an upgrade to MXL technology necessary. Conversely, the Blade 1 component in GT 13 still had approximately 10 years of remaining service life (Vasilyev et al., 2020), resulting in two possible strategies: implementing the MXL upgrade program in the same period or continuing the existing repair strategy until its optimal operational limit. These conditions made the two units suitable comparative cases, enabling a direct evaluation of the investment value of the upgrade strategy versus the repair strategy using equivalent engine specifications and verifiable historical operational data.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5. GAS TURBINE PERFORMANCE					MARCH 2025 DATA			APRIL 2025 DATA		
CODE NO	KKS	DESCRIPTION	UNIT	DATA TYPE	68% LOAD	80% LOAD	90% LOAD	68% LOAD	80% LOAD	90% LOAD
		Data Date			March 21, 2025	March 11, 2025	March 21, 2025	4/14/2025	4/17/2025	4/17/2025
		Data Time			13:00:00	17:00	21:00:00	21:00	17:00	21:00
13	EFFGT4	#4 GT GROSS EFFICIENCY	%	CALC	24.01	25.08	25.58	23.68	24.67	26.23
14	HRGT4	#4 GT GROSS HEAT RATE	kcal/kWh	CALC	3580.58	3428.71	3360.91	3631.68	3485.58	3278.27
15		#4 FUEL GAS FLOW RATE(Vf)	kscm/h	ENTRY	33.98	37.38	43.20	33.50	38.00	43.20
16		#4 Active Power Gen pd meter	MW	ENTRY	87.86	101	119.00	85.40	101.00	122.00

➢ In April 2025, UBP Priok conducted a Performance Test and the results showed that GT 21 experienced an increase in efficiency of up to 26.23% at a load of 122 MW and previously in March at a load of 119 MW it reached an efficiency of 25.58%.

2021-03	2021-04	2021-09	2025-03	2025-04
OLD -T	OLD-T	MXL-1/5	MXL-1/5	MXL1/5
117 MW	119 MW	114 MW	119 MW	122 MW
23.94%	25.40%	23.70%	25.58%	26.23%

Figure 1. Performance Test Report GT 21 PLTGU Priok GT 21 for the period 2021-2025

Figure 1 illustrates the increase in gross efficiency following the MXL blade upgrade. Historical data show that in 2021, before the upgrade, the efficiency of GT 21 at a load of 119 MW was 25.40% (OLD-T). After the upgrade to MXL-1/5 in September 2021, efficiency at a

114 MW load was recorded at 23.70%, then increased to 25.58% at a 119 MW load in March 2025 and further increased to 26.23% at a 122 MW load in April 2025 (Grigore et al., 2024). These results confirmed an efficiency improvement ranging from 0.18% to more than 0.83% compared with the pre-upgrade condition, providing the quantitative basis for calculating natural gas fuel savings and additional electricity production benefits in this techno-economic analysis (Surase et al., 2024).

Based on this background, this study aimed to conduct a quantitative techno-economic analysis to determine the optimal decision between implementing the MXL technology upgrade and continuing the existing repair strategy for GT 13, evaluated from the perspectives of investment value and operational profitability. Specifically, this study calculated the impact of the 0.18% efficiency improvement resulting from the MXL upgrade on natural gas consumption savings and increased electricity production (MWh), compared the total lifecycle costs of both strategies over the 2014–2031 period, and quantified the financial differences between the two alternatives as a basis for measurable and accountable decision-making. The findings of this study are expected to provide a methodological reference for decision-makers in other power generation units facing similar maintenance decisions and contribute to the development of techno-economic analysis frameworks for gas turbine component management in Indonesia.

METHOD

This study employed a techno-economic approach by comparing two investment schemes based on operational data and maintenance history. The analysis consisted of two main stages:

1. Performance Analysis: This stage evaluated the impact of efficiency improvements on Heat Rate (HR) and Specific Fuel Consumption (SFC), including their effects on fuel savings (Gas OpEx Saving) and additional electricity production (MWh).
2. Financial Analysis: This stage compared the investment value of the MXL upgrade with the repair strategy by evaluating total expenditures (investment and repair costs) against the total financial benefits generated from efficiency improvements during the 2014–2031 analysis period.

RESULTS AND DISCUSSION

Performance Analysis and Efficiency Improvement (GT 21)

Based on the results of the *Performance Test* after *upgrading* the GT 21, it was found that there was an increase in turbine efficiency by 0.18%. This increase in efficiency provides two main advantages, namely savings in gas consumption and increased energy production:

Fuel Savings: Increased efficiency results in a gas flow rate savings of 0.071 kg/s. Assuming a historical *Capacity Factor* (CF) of 25.53% (operating time of 2,349.65 hours/year), the total gas mass saved reaches 600,570.54 kg/year. If converted based on the regulation of Certain Natural Gas Prices (HGBT) of 6 USD/MMBTU and an exchange rate of Rp 16,000/USD, the value of this operational savings reaches Rp 2,535,168,396.17 per year.

$$FS = (\Delta\dot{m}_f \times 3600 \times t_{op} \times LHV) \times \frac{P_{gas}}{C_f}$$

Dimana:

- FS = Nilai penghematan finansial tahunan (Rupiah/tahun)
- $\Delta\dot{m}_f$ = Selisih laju aliran massa gas (*before-after* upgrade) (kg/s)
- t_{op} = Waktu operasi ekuivalen per tahun (jam/tahun)
- LHV = *Lower Heating Value* dari gas bumi (kJ/kg)
- P_{gas} = Harga gas bumi (Rupiah/MMBTU)
- C_f = Konstanta konversi energi (1.055.060 kJ/MMBTU)

Table 1. Parameters and Calculation of Gas Fuel Savings Value due to 0.18% Efficiency Increase in GT 21 (Gas Rate Saving Method)

Yes	Parameters/Description	Value	Units	Formula/Description
1	Gas Flow Rate Savings	0,071	kg/second	Field Actual Data (Before-After)
2	Annual Operating Hours	2.349,65	hours/year	Taken from an average CF of 25.53%
3	Time Conversion Constant (Hours to Seconds)	3.600,00	seconds/hour	Raw constant (1 hour = 3600 seconds)
4	Total Gas Mass Saved	600.570,54	kg/year	Gas Flow Rate × 3600 × Operating Time
5	Lower Heating Value (LHV) Gas Bumi	46.392,60	kJ/kg	Actual Caloric Value Data of Gas
6	Total Energy Saved	27.862.028.834,00	kJ/year	Total Gas Mass × LHV
7	Energy Conversion Factor (kJ to MMBTU)	1.055.060,00	kJ/MMBTU	Energy conversion constant
8	Total Energy Saved (MMBTU)	26.408,00	MMBTU/year	Total Energy Saved (kJ) ÷ 1,055,060
9	Certain Natural Gas Prices (HGBT)	6,00	USD/MMBTU	Domestic Regulation
10	Assumption of Exchange Rate	16.000,00	Rp/USD	Macroeconomic Assumptions
11	Fuel Saving Value (Gas OpEx Saving)	2.535.168.396,17	Rp/year	Total Energy (MMBTU) × HGBT (6) × Exchange Rate (16,000)

Source: Actual data on the field of PLTGU Priok and techno-economic calculations.

Table 1 presents the technical parameters and flow of calculation of the gas fuel savings value obtained from the 0.18% efficiency increase in GT 21 *post-MXL upgrade*. Field data shows that the difference in gas flow rate before and after *the upgrade* (*before-after*) was recorded at 0.071 kg/second. By multiplying the reduction rate to the equivalent annual operating time of 2,349.65 hours/year—which is derived from the historical *average capacity factor* of 25.53%—the total gas mass saved is obtained by 600,570.54 kg/year. The energy value saved is then converted using the *Lower Heating Value* of natural gas of 46,392.60 kJ/kg, resulting in a total energy saving of 26,408.00 MMBTU/year. Based on the regulation of

Certain Natural Gas Prices (HGBT) of USD 6/MMBTU at an exchange rate of Rp 16,000/USD, the value of gas fuel savings (*Gas OpEx Saving*) that can be realized reaches **Rp 2,535,168,396.17 per year**, which is the first major component of the total financial benefits of MXL upgrade investments.

Table 2. Capacity Factor Data and Equivalent Operating Hours of GT 21 for the Period 2022–2025

Year of Operation	Capacity Factor (CF)	Equivalent Operating Hours (Full Load)	Equivalent Operating Hours(119 MW Load)
2022	46,44%	4.068,14	4.273,26
2023	32,22%	2822,47	2.964,78
2024	8,21%	719,2	755,46
2025	15,27%	1337,65	1.405,09
Total		8.947,46	9.398,59
Historical Average	**25,53%**	2.236,87	**2.349,65**

Source: PLTGU Priok Trade Report (2022–2025).

Table 2 summarizes the GT 21 equivalent capacity factor (CF) and operating hours data for the period 2022–2025 which is the basis for the operating time assumptions in this analysis. The data shows a significant variation in CF, from a low of 8.21% in 2024 to a high of 46.44% in 2022, with a four-year total full-load equivalent operating hours of 8,947.46 hours. These fluctuations reflect the dynamics of electrical system load demand which are influenced by the availability of new and renewable energy, maintenance schedules, and regional peak load demand. The historical average of CF of 25.53% (equivalent to 2,349.65 hours/year at a load of 119 MW) is used as a representative assumption in the calculation of gas fuel savings in Table 1, so that the results of the analysis reflect the actual operational conditions of the plant in a more realistic and measurable manner.

Table 3. Recap of Net Electricity Production and kWh Difference Due to 0.18% Efficiency Increase GT 21 (2020–2025) (Method of increasing Eff in Kwh is generated)

Year of Operation	Engine	Net Tahunan (kwh)	Increase (%)	Annual Net up 0.18% (kwh)	Difference (kwh)
2020	PRIOK GT 2.1	182.808.231,88	0,18%		
2021	PRIOK GT 2.1	381.531.964,22	0,18%	380.845.206,68	686.757,54
2022	PRIOK GT 2.1	520.311.631,76	0,18%	519.375.070,82	936.560,94
2023	PRIOK GT 2.1	361.207.521,42	0,18%	360.557.347,88	650.173,54
2024	PRIOK GT 2.1	91.233.074,44	0,18%	91.068.854,90	164.219,53
2025	PRIOK GT 2.1	170.327.789,98	0,18%	170.021.199,96	306.590,02
				Total KWH	2.744.301,57
				Net Purchase Price (kwh)	2.200,00
				Total Profit 2021-2025	6.037.463.447,98

Source: Trade Report of the Commercial Division of PLTGU Priok (2020–2025)

Table 3 shows a recap of GT 21's annual net electricity production data along with the projected kWh difference resulting from the 0.18% efficiency increase post-MXL *upgrade* for the period 2020–2025. The kWh difference is calculated as 0.18% of the actual production each year, then becomes the basis for quantifying financial gains in terms of increased energy production. In 2021, the production difference was recorded at 686,757.54 kWh; increased significantly to 936,560.94 kWh in 2022 due to the high *capacity factor*; then 650,173.54 kWh (2023), 164,219.53 kWh (2024), and 306,590.02 kWh (2025), respectively. Cumulatively, the total difference in electricity production over five years reached 2,744,301.57 kWh. Using the net purchase and sale price of IDR 2,200.00/kWh according to the commercial contract agreement, the total value of financial gains from this increase in electricity production is equivalent to IDR 6,037,463,447.98 during the 2021–2025 period. This value, combined with gas fuel savings of Rp 12,675,841,980.86 for 5 years, forms the total accumulated efficiency gains that are used as a deduction in the calculation of the net cost of investment.

Production Profit (kWh): This 0.18% increase in efficiency also contributed to the total net difference in electricity production of 2,744,301.57 kWh during the 2021-2025 period, which is equivalent to a total financial profit of IDR 6,037,463,447.98. *(The total accumulation of efficiency gains over 5 years used in the investment comparison is set at Rp 12,675,841,980.86 referring to the gas flow rate reduction method).*

Overall, the results of the annual kWh data recap from the Priok PLTGU commercial report show that during the 2021–2025 period, the GT 21 post-upgrade MXL was able to produce a total net difference in electricity production of 2,744,301.57 kWh compared to the scenario without *an upgrade*. With a net purchase and sale price of IDR 2,200.00/kWh, the difference in production is equivalent to a total financial gain of IDR 6,037,463,447.98 for five years. When added to the value of gas fuel savings of IDR 2,535,168,396.17 per year (IDR 12,675,841,980.86 for 5 years), the total accumulated profit from the increase in efficiency used as the basis for investment comparison is **IDR 12,675,841,980.86**. This figure is a critical element in determining the net *cost* of each investment scheme in GT 13. The data also shows significant *fluctuations in capacity factors*, ranging from 8.21% in 2024 to 46.44% in 2022, with a historical average of 25.53%, reflecting the variation in the actual operating expenses of plants. These fluctuations also affect the amount of efficiency gains that can be realized from MXL upgrade investments every year.

Investment Value Comparison (GT 13 Case Study)

To answer the hypothesis of whether GT 13 should be *upgraded* in 2021, a comparative simulation of financial expenditure between the two schemes in the 2014-2031 observation period was conducted:

$$LCC = I_0 + \sum_{t-1}^{n} \frac{OPEX_t + C_{repair,t} - B_t}{(1+r)^t}$$

Dimana:

- I_0 = Pengeluaran modal awal (*Capital Expenditure* / Biaya Upgrade MXL)
- $OPEX_t$ = Biaya operasional pemeliharaan rutin pada tahun ke-t
- $C_{repair,t}$ = Alokasi biaya perbaikan berat (*repair/overhaul*) pada tahun ke-t
- B_t = Manfaat finansial (*Benefit*) dari efisiensi bahan bakar pada tahun ke-t
- r = Tingkat suku bunga diskonto (*Discount Rate*)
- n = Umur ekonomis proyek (tahun)

Scheme A: If GT 13 is Upgraded to MXL (Year 2021)

1. Total Investment Expenditure (including taxes, *freight*, *new blades, past repairs, etc.) reached: IDR 84,334,334,333.53.*
2. Profit from Efficiency Increase (2021-2025) (Gas Rate Saving Method): IDR 12,675,841,980.86.
3. **Final Value (Net Cost):** IDR 84,334,334,333.53 - IDR 12,675,841,980.86 = **IDR 71,658,492,352.67**.

Table 4. Details of the Investment Value of GT 13 in the MXL Upgrade Scheme in 2021 (Period 2014–2031)

No	Remarks	Value (USD)	Kurs USD To IDR	Value (IDR)	Payment Year
1	New Blade 1 Standard (2014) Price Value	1.562.250,24	13301	**20.779.490.437,10**	2014
2	Pib & Freight (26%)			5.402.667.513,65	2014
3	New Blade 1 MXL Year Value (2021)	1.900.716,29	14308	**27.195.448.653,01**	2021
4	Pib & Freight (26%)			7.070.816.649,78	2021
	Total Investment Through 2021			**60.448.423.253,53**	
5	Repair-1	522.439,00	18000	**18.807.804.000,00**	2026
6	PIB & Freight Repair			4.890.029.040,00	2026
7	Export -1			188.078.040,00	2025
	Total Investment 2014-2031			**84.334.334.333,53**	

Source: Procurement contract data and maintenance and planning history of the Priok PLTGU

Table 4 provides details of all GT 13 investment expenditure components if the decision *to upgrade* to MXL *blades* is implemented in 2021, covering the 2014–2031 analysis range. Expenditure began in 2014 with the purchase *of* a standard blade worth Rp 20,779,490,437.10 (USD 1,562,250.24 at an exchange rate of Rp 13,301/USD) along with a 26% GDP & *freight* cost of Rp 5,402,667,513.65. In 2021, *a* new MXL blade was purchased worth IDR 27,195,448,653.01 (USD 1,900,716.29 at an exchange rate of IDR 14,308/USD) with a GDP & *freight* of IDR 7,070,816,649.78, bringing the total investment until 2021 to IDR 60,448,423,253.53. Coupled with the 2026 repair cost (IDR 18,807,804,000.00), PIB & *freight repair* (IDR 4,890,029,040.00), and 2025 export costs (IDR 188,078,040.00), the total gross investment expenditure of the *Upgrade* Scheme during 2014-2031 reached **IDR 84,334,334,333.53**. After deducting the accumulated efficiency profit of IDR 12,675,841,980.86, the net *cost* of the *Upgrade* Scheme is **IDR 71,658,492,352.67**.

Scheme B: If GT 13 Resumes Repair Scheme

1. Without *the upgrade*, the GT 13 doesn't get the 0.18% efficiency advantage, but avoids the *large cost of purchasing MXL blades.*
2. **Total Expenditure (Investment + Repair): IDR 66,297,933,022.57**.

Table 5. Details of the Investment Value of GT 13 in the MXL Repair Scheme Without Upgrade (Period 2014–2031)

No	Remarks	Value (USD)	Kurs USD To IDR	Value (IDR)	Payment Year
1	New Blade 1 Standard (2014) Price Value	1.562.250,24	13301	**20.779.490.437,10**	2014
2	PIB & Freight (26%)			5.402.667.513,65	2014
3	Repair-1	446.583,05	14308	**12.779.420.466,01**	2021
4	PIB & Freight Repair			3.322.649.321,16	2021
5	Export -1			127.794.204,66	2020
6	Repair-2	522.439,00	18000	**18.807.804.000,00**	2026
7	PIB & Freight Repair			4.890.029.040,00	2026
8	Export -2			188.078.040,00	2025
	Total Investment 2014-2031			**66.297.933.022,57**	

Source: Procurement contract data and maintenance and planning history of the Priok PLTGU.

Table 5 presents details of all GT 13 expenditure components in the *Repair* Scheme, i.e. scenarios where no MXL *upgrades are carried out* in 2021 and the components continue to undergo repair cycles until the end of their useful life. The initial expenditure in 2014 was identical to the *Upgrade Scheme*, namely the purchase of *standard blades* of Rp 20,779,490,437.10 and the cost of PIB & *freight* of Rp 5,402,667,513.65. The fundamental difference occurred in 2021, where instead of buying a new MXL blade, the GT 13 only underwent the first repair worth IDR 12,779,420,466.01 (USD 446,583.05 at an exchange rate of IDR 14,308/USD) with PIB & *freight* of IDR 3,322,649,321.16 and export costs of IDR 127,794,204.66. In 2026, a second *repair* worth IDR 18,807,804,000.00 is scheduled along with related GDP, *freight*, and export components. The total expenditure of the *Repair* Scheme during 2014-2031 only reached **Rp 66,297,933,022.57**, much lower than the *Upgrade Scheme*, because there was no investment expense for the purchase *of new MXL blades which reached Rp 34,266,265,302.79 (blade price plus PIB &* freight*).*

Difference: In comparison, *the Repair* scheme has a lower total cost. Taking *the Repair* route can save a budget of **IDR 5,360,559,330.10** compared to forcing an *upgrade*.

Table 6. Comparison of the Final Value (Net Cost) of the MXL Upgrade Scheme vs the Repair Scheme in GT 13 (2014–2031)

No	Remarks	Year	Balance	Value (IDR)
1,1	Investment Value (When Blade Upgrade)	2014-2031	Production	84.334.334.333,53
1,2	Profit Value (Efficiency Increase Method)	2021-2025	Advantages	12.675.841.980,86
	Total			71.658.492.352,67
No	**Remarks**	**Year**	**Balance**	**Value (IDR)**
2,1	Investment Value (When Repair Blade)	2014-2031	Production	66.297.933.022,57
	Total			66.297.933.022,57
No	**Remarks**	**Year**	**Balance**	**Value (IDR)**
3,1	Investment Value (When Blade	2014-2031	Production	71.658.492.352,67

	Upgrade)			
3,2	Investment Value (When Repair Blade)	2021-2025	Production	66.297.933.022,57
	Total			(5.360.559.330,10)

Source: Results of techno-economic calculations.

Table 6 summarizes the comparison of the net *cost* between the MXL *Upgrade* Scheme and the *Repair* Scheme in GT 13 as the basis for final decision-making. The net value of the *Upgrade Scheme* was obtained from the total gross investment of IDR 84,334,334,333.53 minus the accumulated efficiency gains of IDR 12,675,841,980.86, resulting in *a net cost* of IDR 71,658,492,352.67. Meanwhile, the *Repair Scheme* did not generate additional efficiency gains, but the total expenditure was only IDR 66,297,933,022.57. The difference between these two net values shows that the *Repair Scheme* is more economical by **IDR 5,360,559,330.10** or around 7.48% of the net cost of the *Upgrade* Scheme. These results unequivocally confirm that in 2021, with the remaining *lifetime of* GT 13 blade components still available for about 10 years, the decision to continue the *repair* scheme is the most financially optimal strategy, able to save more than IDR 5.36 billion for the company.

$$\Delta Cost = LCCupgrade - LCCrepair$$

Based on the *wealth-maximizing principle*, the interpretation of the results of the calculation of the difference in life cycle costs (ΔCost) is as follows. If $\Delta Cost < 0$, then the *upgrade* scheme results in cumulative savings that are greater than the investment costs, making the *upgrade* feasible to implement. Conversely, if $\Delta Cost > 0$, then the *capital cost of upgrading* cannot be covered by the efficiency gains, so maintaining a *repair* strategy is a more financially profitable decision.

Based on a comprehensive comparison of the two schemes in Table 3 and Table 4 above, it can be identified that the difference in costs between the MXL Upgrade Scheme and the *Repair* Scheme on GT 13 is significant. The MXL Upgrade Scheme requires gross investment expenditure of IDR 84,334,334,333.53 including the purchase of *standard blades in 2014 (IDR 20,779,490,437.10), related PIB &* freight *(IDR 5,402,667,513.65), purchase* of MXL blades *in 2021 with an exchange rate of USD 14,308 (IDR 27,195,448,653.01), PIB &* freight upgrade *(IDR 7,070,816,649.78), and* repair costs and exports in 2025–2026 (IDR 23,885,911,080.00). After deducting the efficiency gain of IDR 12,675,841,980.86, the net cost of the *Upgrade Scheme* becomes **IDR 71,658,492,352.67**. Meanwhile, the *Repair* Scheme only requires a total expenditure of **Rp 66,297,933,022.57** during the period 2014-2031, without any additional efficiency gains but also without the burden of new *blade* investment in 2021. The difference between the two schemes is **Rp 5,360,559,330.10** where the *Repair Scheme* proves to be more economical, confirming that continuing *repairs* on GT 13 is a financially optimal decision as long as the *lifetime* of the components is still available.

CONCLUSION

Based on the investment and profitability analysis, it was concluded that UBP's decision in 2021 to upgrade the MXL Blade on GT 21 was appropriate and unavoidable, considering that the standard blade component had reached its end-of-life condition. The MXL upgrade was proven to improve efficiency by 0.18%, resulting in annual natural gas fuel savings of IDR 2,535,168,396.17 and total electricity production gains of IDR 6,037,463,447.98 during the

2021–2025 period. Meanwhile, the decision not to upgrade GT 13 and to continue with the repair scheme was also economically justified because the unit still had an estimated remaining service life of approximately 10 years. The total cost of the GT 13 repair scheme during the 2014–2031 period amounted to IDR 66,297,933,022.57, which was lower than the net cost of implementing the MXL upgrade, amounting to IDR 71,658,492,352.67. Therefore, continuing the repair strategy for GT 13 resulted in cost savings of IDR 5,360,559,330.10 and demonstrated that a condition-based asset management strategy was the optimal approach for maintaining operational reliability while improving the efficiency of power plant investment costs.

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