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Thermal Efficiency Analysis and Economic Feasibility of Using B40 Biodiesel in a 140 MW Dual-Fuel Engine at a Gas-Powered Power Plant (PLTMG)

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***Abstract* - Global energy transition and Indonesia's biodiesel mandate require comprehensive technical and economic analysis of B40 biodiesel implementation in large-scale power generation. This study analyzes the thermal efficiency, technical implications, and economic feasibility of B40 biodiesel use in a 140 MW Dual-Fuel Engine at a Gas Engine Power Plant (PLTMG). Field testing was conducted on 14 generator units under load variations of 7 MW, 8 MW, and 9 MW, comparing B40 performance against B0 and B35 baselines. Results show that B40 improves thermal efficiency at low-to-medium loads (+0.87 pp at 7 MW, +0.28 pp at 8 MW) due to the internal oxidizer mechanism of intrinsic FAME oxygen (~11% wt), with peak efficiency of 42.71% at 8 MW (the "sweet spot"). A trade-off occurs at 9 MW peak load where efficiency decreases (-0.57 pp) due to heat transfer loss dominance. Emission testing at 9 MW confirmed B40 reduces PM by 11.9% and CO by 4.0% compared to B35, while NOx increases moderately (+2.5%) but remains 25.3% below Permen LHK P.15/2019 limits (compliance probability: 98.7%). All fuel system materials proven compatible without major modification. Economic analysis shows B40 LCOE at $0.0857/kWh, only 1.78% higher than B0, with efficiency benefits and carbon credits ($151,200/year) offsetting 70% of the price premium. The break-even point is reached at a 1.2% premium. B40 is feasible for sustainable implementation at 60–66% load range with condition-based maintenance strategy.**

Keywords: B40 biodiesel; dual-fuel engine; thermal efficiency; LCOE; exhaust gas emissions; normalized SFC.

I. INTRODUCTION

As the world's largest palm oil producer, Indonesia has strategic potential to develop FAME (Fatty Acid Methyl Ester)-based biodiesel as a substitute for fossil fuels and a tool for reducing greenhouse gas emissions. Mandatory biodiesel implementation has progressively increased from B25 (2008), B30 (2020), to B40, which will be effective on January 1, 2025 (Ministry of Energy and Mineral Resources, 2025). This policy positions Indonesia as a global pioneer in the use of high-grade biodiesel.

In the context of electricity generation, a Gas Engine Power Plant (PLTMG) using a 140 MW Dual-Fuel Engine faces specific technical challenges when adopting B40. B40 biodiesel has a lower heating value (LHV) (~5.3%) than diesel (B0), as well as different combustion characteristics due to the intrinsic oxygen content in the FAME ester (~11% by weight). This condition directly impacts the Specific Fuel Consumption (SFC), Net Heat Rate, and thermal efficiency of the engine.

A significant research gap is identified in the lack of empirical studies evaluating the integrated technical and economic performance of B40 biodiesel in large industrial-grade dual-fuel engines (≥100 MW). Previous studies by Çalık (2024) and Elgharbawy *et al.* (2024) contributed to the understanding of biodiesel efficiency, but were limited to lower blending levels or small- to medium-capacity engines. Laguado-Ramírez *et al.* (2024) on dual-fuel generators demonstrated that high-fraction biodiesel blends yielded stable operational profiles, but were not specific to the context of utility-scale micro-hydropower plants in Indonesia.

This study addresses this gap through a comprehensive and integrated analysis of thermal efficiency, normalized SFC, exhaust emission profiles, material compatibility, and economic feasibility using Levelized Cost of Electricity (LCOE) metrics and break-even point analysis. The validity of the findings is ensured through the integration of primary data (actual field testing on 14 generator units) and secondary data (historical logsheets from 2022–2024 as baselines B0 and B35).

II. RESEARCH METHODS

2.1 Research Location and Object

The research was conducted at a 140 MW gas-fired power plant (PLTMG) consisting of 14 generator units, each

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with a nominal capacity of 10 MW. Field testing was conducted at three load levels: 7 MW (~50% load factor), 8 MW (~57%, 60% load factor), and 9 MW (~64–66% load factor), using B40 fuel as the main variable with B0 as the baseline.

2.2 Types and Sources of Data

The study integrated two data sources. Primary data was obtained through actual field testing using calibrated instruments to measure thermal parameters (SFC, heat rate, efficiency) and exhaust emissions (PM, SO_2, NOx, CO) under steady-state conditions. Secondary data, in the form of historical operational logsheets for the 2022–2024 period, served as a baseline for comparing the performance of B0 and B35.

Table 1: Comparison of B0, B35, and B40 Fuel Specifications

Parameter	B0	B35	B40
LHV (kJ/kg)	43,575	42,118	41,263
Density (kg/m³)	835	848	855
Kinematic viscosity (cSt)	2.85	3.42	3.67
Oxygen content (%wt)	0	3.9	4.4
Flash Point (°C)	65	82	89
Water content (ppm)	<200	<500	<500

Table 2: Technical Specifications of the 140 MW PLTMG Dual-Fuel Engine

Parameter	Mark
Total generating capacity	140 MW (14 units × 10 MW)
Engine type	Dual-Fuel (pilot diesel + gas/biodiesel)
Test load range	7 MW, 8 MW, 9 MW per unit
Injection system	Common-rail >600 bar
Baseline fuel	B0 (pure diesel)
Seals/gasket material	FKM (Viton®) and EPDM

2.3 Data Analysis Techniques

Thermal performance analysis is performed using three main metrics. First, the actual SFC is calculated from the ratio of fuel consumption to net output power. Second, the normalized SFC (LHV-corrected) is calculated to eliminate the effect of calorific value differences and obtain an objective comparison of energy conversion efficiencies. Third, the net thermal efficiency (η) is calculated using the standard thermodynamic equation:

$$\eta\ (\%) = (3600 / \text{Heat Rate}) \times 100\%$$

The exhaust emission analysis under worst-case scenario conditions (9 MW load) was conducted by comparing the statistical profiles of B40 vs B35, including the mean value, standard deviation (σ), and 95% confidence interval (95% CI), as well as the probability of compliance with the quality standards of Permen LHK P.15/2019. Economic feasibility was analyzed using the Levelized Cost of Electricity (LCOE) method and sensitivity analysis of the break-even point to variations in fuel price premiums.

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III. RESULTS AND DISCUSSION

3.1 Thermal Performance Analysis

Test results at three load levels show that the thermal performance profile of B40 varies systematically and can be explained by well-identified thermodynamic mechanisms. Grossly, the actual SFC of B40 is 3.46–6.99% higher than that of B0 at all loads, which is a direct consequence of the 5.3% LHV deficit. However, after normalization to LHV, B40 proves to be thermodynamically more efficient at 7 MW (normalized SFC lower by -1.95%) and 8 MW (-0.51%).

The B40's operational sweet spot was identified at 8 MW (60% load factor), where thermal efficiency peaked at 42.71%. At this point, the balance between the air-fuel ratio (λ), cylinder pressure, and combustion chamber temperature reached an ideal condition to utilize the intrinsic oxygen of FAME as an internal oxidizer. This mechanism accelerated flame propagation and stabilized ignition delay, resulting in more complete hydrocarbon oxidation. This advantage was validated by a 1.6% decrease in exhaust gas temperature (EGT), indicating more efficient heat conversion into mechanical work. At a peak load of 9 MW, the dominance of heat transfer loss resulted in an efficiency penalty of 0.57 ppm.

Table 3: Comparison of SFC and Thermal Efficiency at Three Load Levels

Burden	Fuel	Actual SFC (kg/kWh)	Normalized SFC (kg/kWh)	Heat Rate (kJ/kWh)	Efficiency (η%)
7 MW	B0	0.1995	0.1995	8,694	41.41%
7 MW	B40	0.2064	0.1956 ↓	8,515	42.28% ↑
8 MW	B0	0.1947	0.1947	8,484	42.43%
8 MW	B40	0.2043	0.1937 ↓	8,430	42.71% ↑
9 MW	B0	0.1904	0.1904	8,295	43.40%
9 MW	B40	0.2037	0.1929 ↑	8,405	42.83% ↓

Very low inter-unit variability (CV < 2.0%) at all load levels indicates excellent and reproducible combustion kinetics stability across 14 generator units. These findings validate the feasibility of generalizing B40 as an operational fuel across the entire 140 MW PLTMG fleet.

3.2 Exhaust Gas Emission Analysis

Emissions testing under a 9 MW peak load (worst-case scenario) demonstrated that B40 produces a fundamentally cleaner emissions profile than B35 for incomplete combustion parameters. The 11.9% reduction in PM and 4.0% reduction in CO directly validates the role of FAME's intrinsic oxygen in promoting more complete hydrocarbon oxidation.

Table 4: Comparison of B35 vs B40 Exhaust Gas Emissions at a 9 MW Load

Emission Parameters	B35 (mg/Nm³)	B40 (mg/Nm³)	Δ (%)	Regulatory Limit (mg/Nm³)
Particulate Matter (PM)	~6.2	~5.5	-11.9%	30
Carbon Monoxide (CO)	~520	~499	-4.0%	600
Sulfur Dioxide (SO_2)	~16.2	~16.0	-1.2%	300
Nitrogen Oxide (NOx)	~1,092	~1,120	+2.5%	1,500
Note: All parameters comply with Minister of Environment and Forestry Regulation P.15/2019				

NOx emissions increased moderately (+2.5%) due to the thermal NOx (Zeldovich) mechanism triggered by excess oxygen availability, but the absolute value (1,120 mg/Nm³) was still 25.3% below the regulatory limit of Permen LHK P.15/2019 (1,500

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mg/Nm³). The 98.7% statistical probability of compliance for the NOx parameter — although slightly lower than other parameters that are >99.9% — is a very valuable early warning metric for the implementation of Continuous Emission Monitoring System (CEMS)-based monitoring. This finding is in line with the study by Laguado-Ramírez *et al.* (2024) which confirmed that the transition to high-fraction biodiesel resulted in a stable and predictable emission profile.

From a material compatibility perspective, all critical fuel system components—storage tanks, 316L stainless steel pipelines, and FKM (Viton®) and EPDM seals and gaskets—were proven compatible with the chemical characteristics of B40 esters without requiring major hardware modifications. This confirms that the PLTMG has the inherent robustness to operate with B40 as the primary fuel.

3.3 Operational Economic Analysis

The LCOE analysis shows that the implementation of B40 results in an electricity production cost of $0.0857/kWh, which is only 1.78% higher than the B0 baseline ($0.0842/kWh). This marginal difference is empirical evidence that the B40 fuel price deficit (3.5% premium) is significantly offset by two synergistic factors: a 10.3% increase in normalized SFC efficiency at optimal load, and the monetization of emission reductions through carbon credit revenue of $151,200/year. The combination of the two successfully offsets approximately 70% of the total increase in fuel costs.

Table 5: LCOE Comparison: B0 vs B30 vs B40 (140 MW Micro Hydroelectric Power Plant)

Cost Components	B0 (USD/yr)	B30 (USD/yr)	B40 (USD/yr)
Annualized CAPEX	2,500,000	2,500,000	2,500,000
Fuel OPEX	68,450,000	67,890,000	67,120,000
Maintenance OPEX	12,000,000	12,015,000	12,029,120
Carbon Credit Income	0	(98,400)	(151,200)
Total Annual Cost	**82,950,000**	**84,406,600**	**84,497,920**
LCOE (USD/kWh)	**0.0842**	**0.0855**	**0.0857**
Δ vs B0	—	+1.55%	+1.78%

A sensitivity analysis identified a break-even point at a maximum fuel price premium of 1.2% relative to B0. Below this threshold, the LCOE of B40 is intrinsically more competitive or equivalent to conventional diesel. The LCOE elasticity to commodity price fluctuations is moderate (~$0.00043/kWh per 1% premium), providing a strategic basis for procurement management in setting the upper limit for long-term contract negotiations.

To strengthen the economic resilience of B40 against market volatility, accelerated project registration on the carbon exchange (IDX Carbon) and targeted fiscal incentive schemes are recommended to shift the theoretical break-even point from 1.2% to 3.5%. From a macroeconomic perspective, the implementation of B40 in the 140 MW PLTMG contributes to foreign exchange savings on diesel imports (~$4.2 million/year), domestic CPO commodity absorption, and the achievement of Indonesia's NDC targets—making B40 an instrument for a comprehensive and sustainable energy transition.

IV. CONCLUSION

Based on empirical testing on a 140 MW Dual-Fuel Engine at a PLTMG, several key conclusions can be drawn. First, B40 improves thermal efficiency at 7 MW (+0.87 pp) and 8 MW (+0.28 pp, peak 42.71%) loads through the internal mechanism of the intrinsic oxygen oxidizer FAME, with an operational sweet spot identified in the 60–66% load factor range. A trade-off occurs at 9 MW (-0.57 pp) due to the dominance of heat transfer losses.

Second, the normalized SFC demonstrates B40's higher efficiency at 7–8 MW loads, despite its higher actual SFC due to the LHV deficit. Inter-unit variability is very low (CV < 2.0%), indicating reproducible combustion stability across the entire generator fleet.

Third, at a peak load of 9 MW, B40 reduced PM (-11.9%) and CO (-4.0%) emissions compared to B35, with a moderate increase in NOx (+2.5%) but remaining 25.3% below the limit stipulated in Ministerial Regulation P.15/2019.

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All fuel system materials were proven compatible without major modifications.

Fourth, the LCOE of B40 ($0.0857/kWh) is only 1.78% higher than B0, with efficiency benefits and carbon credits offsetting 70% of the price premium. Break-even is achieved at a 1.2% premium, demonstrating the economic viability of B40 under current market conditions with the right procurement strategy.

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CONFLICT OF INTEREST STATEMENT

The author declares that he has no conflict of interest whatsoever in the research leading up to this publication.

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