Optimization of Waste Heat Recovery Utilizing Organic Rankine Cycle at Bangkanai Gas Engine Power Plant PT PLN Nusantara Power UP Kalselteng

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Abstract— **Bangkanai Gas Engine Power Plant exhibits a substantial waste heat potential within its exhaust gas, with manifold temperatures post-turbocharger ranging from 386.40 °C to 515.00 °C. Currently, this high temperature thermal energy is underutilized. This study aims to evaluate the technical and financial feasibility of integrating an Organic Rankine Cycle (ORC) bottoming system into the exhaust stack of PLTMG Bangkanai. A dynamic computational model was constructed using the MATLAB R2023a-CoolProp platform. The thermodunamic property of the mixed flue gas the JANAF/NIST Shomate Polynomial functions. The simulation evaluated four working fluids (R245fa, Toluene, Benzene, R1233zd(E)) across three optimization scenarios, constrained by an acid dew point stack safety limit (≥ 160.00 °C). The results reveal that R1233zd(E) yields the most superior performance, maintaining an absolute dry vapor phase at the turbine outlet(X_{out}=\ 1.00) and completely eliminating turbine blade cavitation risks. The integrated ORC system successfully harvested a peak net clean power output 6,152.40 kW. This addition elevated the overall system thermal efficiency from 38.50 % to 42.10 % and reduced the Specific Gas Comsumption (SGC) by 3.66%. Eviromental assessment utilizing the Higher-Tier Tier 3 IPCC direct stoichiometry approach indicates a greenhouse gas mitigation potential of 1,382.328 Tons of CO2 per year. Financial feasibility analysis was conducted over a 20-year Power Purchase Anreement (PPA) horizon, calibrated with a 10.00% Cost Of Capital (CoC) and a flat exchange rate of Rp17,500/USD. The initial Capital Expenditure (CapEx) allocation of Rp236.87Billion is economically viable, generating a positive Net Present Value (NPV) of +Rp49.72 Billion, an Internal Rate of Return (IRR) of 14.52%, a Benefit-Cost Ratio (B/C) of 1.177, and a Payback Period (PBP) of 8.2 years.**

Keywords— Organic Rankine Cycle, waste heat recovery, PLTMG, energy optimization, flue gas, thermal efficiency, emissions, Thermodynamics, MATLAB-CoolProp.

I. INTRODUCTION

Electrical energy holds a strategic role in supporting economic, social, and national developmental growth. As population density and industrial sectors expand, the national power grid demands not only an increase in capacity but also highly efficient, reliable, and sustainable operations. As of 2024, Indonesia's national power generating capacity reached 100,649 MW, heavily dominated by fossil fuel-based thermal power plants at 86.24%, while new and renewable energy (EBT) contributions lagged at 13,76% [1]. This overwhelming reliance on fossil fuel combustion renders the power sector a primary contributor to greenhouse gas emissions, particularly carbon dioxide (CO_2), driving global climate change and environmental degradation. Consequently, transforming the energy infrastructure toward cleaner, low-carbon systems has become an unavoidable imperative

In response to these energy transition challenges, the Indonesian government alongside PT PLN (Persero) established the National Electricity Supply Business Plan (RUPTL) 2025-2034, famously termed the "Green RUPTL". This planning framework mandates a higher renewable energy mix, reductions in carbon emission intensities, and comprehensive efficiency enhancements within existing thermal fleets [2]. Improving the thermal efficiency of existing power units has been proven to mitigate baseline carbon emissions by at least 8% through a combination of structured technical interventions and waste heat harvesting[3].The Bangkanai Gas Engine Power Plant (PLTMG), operated by PT PLN Nusantara Power UP Kalselteng, serves as a critical infrastructure asset supplying electricity to the Interconnected Kalimantan Grid. PLTMG Bangkanai possesses an installed capacity of 155 MW, supported by 16 units of Wärtsilä 20V34SG reciprocating gas engines. As a simple-cycle fossil-fueled thermal plant, its primary thermodynamic conversion process leaves a massive portion of input energy unutilized, rejecting it directly to the atmosphere as high-temperature thermal waste through the exhaust stream.

According to Net Plant Heat Rate and Net Capacity verification reports issued by the PT PLN (Persero) Certification Center, the flue gas entering the exhaust stack after passing through the turbocharger manifold maintains a high temperature between 480.60 °C and 515.00 °C [4]. Discharging this thermal volume directly into the atmosphere reflects a low total energy utilization factor and induces local thermal pollution. The urgency to optimize energy utilization at PLTMG Bangkanai is further exacerbated by strict fuel gas supply contracts. Based on the Gas Sales and Purchase Agreement, the maximum Daily Contract Quantity (DCQ) is strictly limited to 22 BBTUD. To optimize this dynamic daily quota, the grid dispatcher (PT PLN UP2B Kalselteng) enforces an internal energy storage management scheme: during off-peak hours, roughly 16.8 BBTUD is allocated to run the gas engines continuously for base-load coverage, while the remaining 5.2 BBTUD is directed to a Compressed Natural Gas (CNG) plant to be compressed and stored in tube skids. This dynamic operational constraint, coupled with

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fluctuating unit availability and abundant waste heat, opens an excellent opportunity for the deployment of a Waste Heat Recovery System (WHRS).

Among various mid-to-low temperature waste heat recovery technologies, the Organic Rankine Cycle (ORC) is recognized as one of the most reliable and efficient methods[5]. Unlike conventional Rankine cycles that rely on water as the working medium, an ORC system utilizes high-molecular-weight organic fluids characterized by low boiling points and appropriate critical pressures. This allows the system to extract thermal energy from gas streams with superior efficiency. Integrating modular ORC bottoming systems onto PLTMG Bangkanai transforms the simple-cycle facility into a highly efficient combined-cycle power plant, generating clean, cost-free electricity without expanding the contractual gas fuel quota.

The increasing complexity of organic fluid thermophysical behaviors, which are highly sensitive to microscopic pressure and temperature shifts, necessitates a high-precision macroscopic computational model. This study implements an advanced programming algorithm based on the MATLAB platform, linked directly to the international thermophysical property database CoolProp, to accurately simulate the operational performance of the ORC system[6]. Through this dynamic computational approach, the net increases in total thermal efficiency, specific gas consumption savings, and quantitative annual CO_2 emission reductions are mapped comprehensively.

Furthermore, the strategic importance of this energy enhancement aligns with the progressive power demand growth across the Interconnected Kalimantan Grid. Grid evaluation logs reveal that the peak load in 2025 surged to 2,031 MW, reflecting a sharp 12% increase compared to the 2024 peak of 1,812 MW [7]. The minimum spinning reserve margin dropped to an alarming low of 58.2 MW, with a daily average reserve of 255 MW. Given these grid vulnerabilities and the lengthy timeline required to construct new greenfield power stations, maximizing energy exploitation via an integrated ORC system at PLTMG Bangkanai represents a rapid, cost-effective, and highly pragmatic engineering solution.

Therefore, this research aims to comprehensively evaluate the thermodynamic properties and total waste heat potentials of the Wärtsilä 20V34SG exhaust stream under fluctuating daily load cycles. It systematically analyzes combined-cycle system parameters, identifies the optimal organic working fluid under strict acid dew point constraints, and establishes a robust techno-economic validation model verifying the technical and financial feasibility of the capital investment.

II. METHODS

This study utilizes a rigorous quantitative methodology combining empirical industrial data tracking with advanced numerical modeling and dynamic computational simulations. The engineering framework evaluates the co-generation performance of an ORC system attached to the exhaust stack of PLTMG Bangkanai, ensuring the reproduction of results based on the specifications detailed below.

2.1 Object and Data Inventory

The research object centers on the 16-unit Wärtsilä 20V34SG gas engine fleet at PLTMG Bangkanai, located in Karendan Village, Barito Utara, Central Kalimantan (Latitude: -0.622442, Longitude: 115.136767). Technical data inputs are divided into primary and secondary sources:

- Primary Data: Flue gas chemical composition and volumetric fractions were extracted directly from the plant exhaust stacks using a calibrated Sauermann Combustion Analyzer. Hourly operational logsheets across a full 24-hour cycle were recorded to map real-time load profiles, exhaust temperatures, and baseline gas consumption.
- Secondary Data: Baseline performance benchmarks were acquired from the official Net Plant Heat Rate and Performance Test Report certified by the PT PLN (Persero) Certification Center. Material properties and thermodynamic coefficients were obtained from the JANAF/NIST Shomate polynomial database and the open-source CoolProp fluid library.The physical and electrical characteristics of the target Wärtsilä 20V34SG engine units under nominal conditions are summarized in Table 1.

Table 1. Technical Specifications of Wärtsilä 20V34SG Gas Engine [8]

Engine Parameter	Nominal Specification / Value
Engine Type	4-Stroke, Reciprocating Internal Combustion Engine
Cylinder Configuration	V-20 Cylinder
Cylinder Bore	±340 mm
Piston Stroke	±400 mm
Nominal Rotational Speed	±750 rpm (50 Hz Grid Frequency)
Nominal Electrical Output	9.8 – 10.0 MW per unit
Electrical Efficiency (LHV)	Up to 49.00%
Exhaust Gas Temperature Range	400 °C – 450 °C (Continuous block operation)

2.2 Thermophysical Characterization of Flue Gas

To compute the available thermal power from the exhaust stream dynamically, the flue gas mixture's properties must be calculated as a function of temperature (T). First, the operational capacity factor (CF) of a single engine unit is defined as:

$$CF = \frac{P_{akttual}}{P_{nominal}} \times 100\ \%$$

Where $P_{akttual}$ is the instantaneous electrical output and $P_{nominal}$ is the rated capacity. Next, the average molar mass of the flue gas mixture M_{mix} is calculated based on the ideal gas equilibrium law:

$$M_{mix} = (x_{O2}\ x\ M_{O2}) + (x_{CO2}\ x\ M_{CO2}) + (x_{N2}\ x\ M_{N2})$$

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Where x_i represents the volumetric mol fraction of individual gas species measured by the analyzer, and M_i) represents their respective molecular weights. The specific heat capacity $C_{p,mix}$ of the mixture is computed dynamically via the Shomate polynomial model[9] :

$$C_{p,i} = A + B \cdot t + C \cdot t^2 + D \cdot t^3 + \frac{E}{t^2}$$

Where (A, B, C, D, E) are the standardized JANAF/NIST constants for each component gas.

2.3 ORC Simulation and Component Modeling

The simulation script was developed within the MATLAB R2023a environment, linking directly to CoolProp to capture real-time state changes under steady-state conditions. The ORC loop consists of four primary components governed by the First Law of Thermodynamics[10]:

1. Evaporator (Heat Input): Extracts thermal power Q_{WHR} from the flue gas to vaporize the high-pressure organic fluid:

$$Q_{WHR} = \dot{m}_{exh} . C_{p,mix} . (T_{exh,in} - T_{exh,out}) = \dot{m}_{ORC} . (h_3 - h_2)$$

2. Turbine / Expander (Work Output): The vapor expands to produce gross mechanical power, driving a generator:

$$W_{turbin} = \dot{m}_{ORC} . (h_3 - h_{4,act}) . \mu_{gen}$$

Where $h_{4,act}$ is calculated using the turbine isentropic efficiency μ_{turbin}

3. Condenser (Heat Rejection): Rejects heat to an external cooling medium, restoring the organic fluid to a saturated liquid state:

$$Q_{out} = \dot{m}_{ORC} . (h_4 - h_1)$$

4. Working Fluid Pump (Work Input): Compresses the liquid fluid back to the high-pressure evaporator level::

$$Q_{out} = \frac{\dot{m}_{ORC} . (h_{2,is} - h_1)}{\mu_{pump}}$$

Four distinct organic working fluids were evaluated under identical heat source parameters: R245fa, Toluene, Benzene, and R1233zd(E). The parameters were optimized across three core scenarios by adjusting evaporator pressure, turbine isentropic efficiency, generator efficiency, and the evaporator pinch point temperature difference.

2.4 Safety and Technical Constraints (Decision Points)

Before generating net output metrics, every simulation scenario must satisfy two strict structural safety criteria [11],[12]

- Acid Dew Point Prevention Constraint: To avoid catastrophic low-temperature acid corrosion along the carbon-steel surfaces of the heat exchanger and the main exhaust stack, the flue gas exit temperature must remain above the acid dew point threshold of the local natural gas supply : $T_{flue,out} \geq 160$ ℃
- Turbine Blade Cavitation Elimination Constraint: To prevent high-velocity liquid droplet impingement and erosion on the turbine expander blades, the fluid phase at the turbine discharge must remain strictly within the superheated or absolute dry vapor region: ($X_{out} = 1.00$). Scenarios violating either boundary are immediately rejected by the algorithm, triggering an automated parametric shift in the evaporator pressure or pinch-point constraints.

2.5 Ecological and Financial Evaluation Models

Skenarios satisfying all technical safety constraints proceed to environmental and economic validation. The annual carbon dioxide reduction ΔM_{CO_2} is calculated using the Higher-Tier 3 IPCC direct stoichiometry method, tracking the fuel savings achieved by substituting simple-cycle grid power with clean ORC power generation [13] :

$$\Delta M_{CO_2} = W_{net,ORC} . \Delta SGC . EF_{fuel} . Hours$$

Where EF_{fuel} is the localized natural gas carbon emission factor.

Financial feasibility is modeled over a 20-year Power Purchase Agreement (PPA) operational horizon. The investment is evaluated against a Capital Expenditure (CapEx) of Rp236.87 Billion[14], a weighted Cost of Capital (CoC) discount rate (r) of 10.00%, and a baseline foreign currency conversion rate fixed at Rp17,500/USD. Financial metrics are computed via the following mathematical formulations [15], [16]:

- Net Present Value (NPV):
$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1 + r)^t} - l_0$$
- Profitability Index (PI):
$$PI = \sum_{t=1}^{n} \frac{CF_t \frac{CF_t}{(1+r)^t}}{CF_0}$$
- Internal Rate of Return (IRR) : The discount rate causing the NPV to equal exactly zero:
$$IRR = i_1 + (\frac{NPV_1}{NPV_1 - NPV_2}) x (i_2 - i_1)$$
- Payback Period (PBP): The exact duration required for the cumulative discounted net cash inflows to fully recover the initial CapEx injection.

III. Results and Discussion

3.1 Parametric Thermophysical and Fluid Selection

Based on the simulation results, the value of the mixture specific heat capacity ($C_{p,mix}$) decreases by 2.84% from 1.1289 kJ/kg·K (CF = 25.68%) to 1.0968 kJ/kg·K at full-load (CF = 92.98%). This drop provides a clear theoretical justification of the Wärtsilä 20V34SG turbocharger behavior, where the turbine extracts energy maximally at full capacity. Under full-load conditions, the total accumulated available thermal power from the exhaust stacks climbs linearly from

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19.58 MW_{th} at off-peak hours to a peak of 56.80 MW_{th} during peak loads.

If compared quantitatively to previous literature, the waste heat scale harvested at PLTMG Bangkanai is significantly higher. For instance, a similar study by Valencia Ochoa et al.[17] on a small 2 MW natural gas engine only detected an average exhaust heat rate of 0.514 MW_{th}. The massive cylinder configuration of the Wärtsilä 20V34SG fleet allows a massive mass flow density, validating the thermodynamic recovery models Proposed by Douadi et al. [18] and Varshil & Deshmukh [19], which state that waste heat potentials in large-scale utilities are primarily driven by flue gas mass flow rates rather than temperature gradients.

Figure 1 illustrates the comparative dynamic mass flow rate and net power output capabilities mapped by MATLAB for the evaluated fluids under full-load conditions.

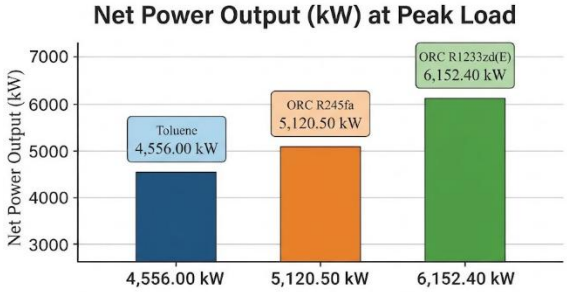


Figure 1. Peak Net Power Generation across Candidate Fluids

When applied across the combined configuration of the 16-unit Wärtsilä fleet, the R1233zd(E) modular design produced a peak net clean electricity output of 6,152.40 kW without requiring a single unit of additional fuel gas input.

3.2 Plant Efficiency Gains and Environmental Mitigation

Integrating the secondary ORC loop effectively converts the facility from a simple-cycle power plant into a combined-cycle system. The technical enhancements gained from this integration are detailed in Table 2.

Table 2. System Performance Comparison

Performance Parameter	Baseline Simple-Cycle	Integrated WHRS-ORC Combined-Cycle	Net Technical Improvement
Total Plant Thermal Efficiency	38.50%	42.10%	+3.60% (Absolute increase)
Specific Gas Consumption (SGC)	Baseline Contract	Optimized Level	-3.66% (Fuel saving efficiency)

Integrating the secondary ORC loop effectively converts the simple-cycle facility into a highly efficient combined-cycle system. The absolute plant thermal efficiency increased by 3.60% (from 38.50% to 42.10%), which effectively drops the Specific Gas Consumption (SGC) by 3.66% across all load profiles. This fuel saving successfully resolves the local gas contract quota limitation of 22 BBTUD. Applying the Tier 3 IPCC direct stoichiometry approach, the clean energy generated by the R1233zd(E) ORC system offsets fossil-fuel baseline emissions, preventing the release of 1,382.328 Tons of CO_2 per year.

The exclusion of an intermediate thermal oil loop (*direct coupling*) and the low-GWP properties of R1233zd(E) prevent secondary carbon penalties. This aligns with advanced Life Cycle Assessments (LCA) conducted by Valencia Ochoa *et al.*,[17] which proved that removing structural thermal oil loops isolates up to 92% of eco-toxicity and global warming impacts throughout the life cycle of waste heat recovery projects.

3.3 Economic Feasibility and Investment Validation

To evaluate the financial viability of the required Rp236.87 Billion Capital Expenditure (CapEx), a comprehensive cash flow ledger was compiled. The model accounts for yearly operational expenditures (OpEx), insurance overheads, and maintenance costs against the financial gains from fuel savings and increased electricity generation. Table 3 presents the economic indicators compiled over the 20-year PPA horizon at a 10.00% Cost of Capital discount rate.

Financial Indicator	Calculated Project Value	Standard Boundary Requirement	Economic Decision
Net Present Value (NPV)	+Rp49.72 Billion	(>0 (Positive Yield)	Highly Feasible
Internal Rate of Return (IRR)	14.52%	> CoC (10.00%)	Highly Feasible
Profitability Index (PI / BCR)	1.177	(>1.00 (Capital Efficiency)	Highly Feasible
Discounted Payback Period (PBP)	8.2 Year	< Horizon (20 Years	Highly Feasible

The Net Present Value yielded a highly favorable result of +Rp49.72 Billion, satisfying the core economic requirement for capital deployment. The calculated Internal Rate of Return (IRR) of 14.52% stands well above the 10.00% weighted Cost of Capital, demonstrating that the project remains highly resilient against macroeconomic fluctuations.

The Profitability Index of 1.177 confirms that every single Rupiah of capital invested yields Rp1.177 in discounted returns, indicating excellent capital efficiency. The initial investment is fully recovered within 8.2 years, leaving the remaining 11.8 years of the PPA operational contract as clear financial profit for the utility operator.

This financial performance confirms a strong *economies of scale* effect triggered by the high capacity of the Wärtsilä fleet. According to the thermoeconomic optimization principles outlined by Valencia Ochoa *et al.*[20], using

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Particle Swarm Optimization (PSO) on stationary internal combustion engines can safely compress payback horizons to under 6 years for smaller applications. For a massive multi-unit asset like PLTMG Bangkanai, the large volume of annual *avoided fuel expenditures* (Rp42.92 Miliar saved per year) creates robust cash inflows that easily cushion macroeconomic shocks and currency volatilities.

IV CONCLUSION

This study confirms that the integration of an Organic Rankine Cycle (ORC) system at PLTMG Bangkanai is highly feasible both technically and financially. The exhaust stream of the Wärtsilä 20V34SG engines holds substantial underutilized thermal energy, with temperatures post-turbocharger reaching up to 515.00 °C. The MATLAB-CoolProp simulation successfully identified R1233zd(E) as the optimal organic working fluid. It meets all safety boundaries, including maintaining an absolute dry vapor phase $X_{out} = 1.00$ to prevent turbine blade erosion and keeping flue gas temperatures above the 160.00 °C acid dew point limit. At peak operation, the system harvests 6,152.40 kW of clean electricity, raising the plant's thermal efficiency from 38.50% to 42.10% and decreasing specific gas consumption by 3.66%. Environmentally, the system offsets 1,382.328 Tons of CO_2 emissions annually. Financially, the project's Rp236.87 Billion CapEx yields an NPV of +Rp49.72 Billion, an IRR of 14.52%, and a Profitability Index of 1.177, with a capital payback period of 8.2 years. This research establishes a highly reproducible, mathematically verified co-generation framework that demonstrates how heavy utility infrastructures can achieve deep decarbonization and strong financial returns simultaneously.

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