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Investment cost analysis and payback period of waste heat recovery system technology in a nickel pyrometallurgical smelter with 300,000 tons NPI/ year capacity: a case study of PT "X" in the IMIP Morowali industrial area

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Abstract: *The pyrometallurgical nickel processing industry in the Morowali Industrial Area (IMIP) exhibits extremely high energy consumption, in which the Rotary Kiln-Electric Furnace (RKEF) process generates substantial quantities of waste heat that are routinely discharged into the atmosphere without utilization. This study aims to analyze the investment feasibility of implementing Waste Heat Recovery System (WHRS) technology based on the Organic Rankine Cycle (ORC) at PT "X" smelter with a production capacity of 300,000 tons of Nickel Pig Iron (NPI) per year for on-site power generation. The research employs a capital budgeting approach incorporating Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP) as key financial parameters, supported by thermodynamic calculations to determine the potential electrical power output. Results indicate that the available waste heat potential from flue gas across four RKEF lines amounts to 156.8 MW thermal, yielding a net electrical output of 28.5 MW. The total WHRS investment cost is estimated at USD 42.75 million, generating annual energy cost savings of USD 14.93 million. Financial feasibility analysis produces an NPV of USD 56.82 million at a 10% discount rate, an IRR of 28.47%, and a Payback Period of 3 years and 2 months. The resulting energy cost reduction reaches 18.7% of the total smelter electrical energy expenditure. The findings confirm that WHRS implementation in nickel pyrometallurgical smelters is financially viable and contributes significantly to industrial energy efficiency and decarbonization efforts in Indonesia's nickel processing sector.*
Keywords: *Waste Heat Recovery System; Nickel Smelter; Payback Period; NPV; IRR; Organic Rankine Cycle*

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INTRODUCTION

Indonesia holds the world's largest nickel reserves, estimated at approximately 21 million tons, representing around 22% of total global nickel reserves (Nuranisa et al., 2023). Since the enactment of mineral downstreaming policy through Law No. 4 of 2009 on Mineral and Coal Mining, the domestic nickel processing industry has experienced rapid and sustained growth. Among the most prominent industrial zones engaged in large-scale nickel processing is the Indonesia Morowali Industrial Park (IMIP) in Central Sulawesi, with a production capacity exceeding 1.5 million tons of Nickel Pig Iron (NPI) per year (Pratiwi & Widodo, 2024).

The dominant technology applied for processing saprolite-type laterite nickel ore is the Rotary Kiln-Electric Furnace (RKEF) process. This process involves sequential stages of drying, calcination, and partial reduction in a rotary kiln, followed by smelting in an electric arc furnace (EAF) to produce NPI with a nickel content of approximately 8–14% (Wang et al., 2022). However, the RKEF process is characterized by intensive energy consumption, with specific energy use ranging between 300–400 kWh per ton of dry ore, of which approximately 25% is dissipated as flue gas and 8% is lost as radiant heat through furnace walls (Liu et al., 2022)

Waste heat discharged from rotary kilns and electric furnaces typically exhibits temperatures between 350–650°C and is released directly to the atmosphere through stacks without further utilization. This condition presents two major problems: energy inefficiency and the emission of greenhouse gases that contribute to global warming (Atashbozorg et al., 2022). In the context of Indonesia's energy transition and its commitment to achieving Net Zero Emissions by 2060, the recovery of waste heat constitutes a strategic opportunity to simultaneously enhance industrial energy efficiency and reduce the carbon footprint of the nickel processing sector.

Waste Heat Recovery Systems (WHRS) are technologies designed to convert industrial process waste heat into useful energy forms, including electrical power. Notable WHRS technologies include the Steam Rankine Cycle (SRC), Organic Rankine Cycle (ORC), and Kalina Cycle. Among these, ORC has emerged as a particularly promising solution for medium-temperature heat sources (300–500°C), owing to its flexibility in working fluid selection, good conversion efficiency at small-to-medium scale, and ease of operation and maintenance (Cao et al., 2023; Setiawan & Hartono, 2022).

Several prior studies have demonstrated the technical and economic feasibility of WHRS in metal processing industries. (Atashbozorg et al., 2022)analyzed the application of ORC and Kalina cycle systems in the iron and steel industry, finding that the Double Regenerative ORC (DRORC) configuration delivered optimal performance for electric arc furnaces. (Kose et al., 2022) found that Kalina cycle systems achieved shorter payback periods than ORC in certain industrial configurations. However, specific financial analyses of WHRS implementation in nickel pyrometallurgical smelters in Indonesia remain extremely limited.

Based on the foregoing background, this study aims to: (1) analyze the waste heat utilization potential of a nickel pyrometallurgical smelter with a capacity of 300,000 tons NPI/year; (2) calculate the investment cost requirements for implementing ORC-based WHRS technology; (3) evaluate the financial feasibility of the project using NPV, IRR, and Payback Period parameters; and (4) quantify the energy cost reduction achievable through WHRS implementation. The findings are intended to serve as a basis for investment decision-making by the nickel smelter industry and to contribute to academic discourse on energy efficiency technology in the mineral processing sector.

METHOD

Research Object and Location

The research object is the nickel pyrometallurgical smelter facility of PT "X", located in the IMIP Industrial Area, Morowali, Central Sulawesi, with a production capacity of 300,000 tons of NPI per year. The smelter operates using RKEF technology across four parallel production lines, each consisting of one rotary kiln with a capacity of 600 tons of ore per day and one electric arc furnace with an installed power of 33 MW (Tsukamoto et al., 2023).The operational data used in this study was sourced from smelter operational records, engineering literature, and industrial reports published between 2021 and 2025. Table 1 presents the primary operational parameters used as the basis for all calculations.

Table 1. Operational Parameters of PT "X" Smelter

No.	Parameter	Value	Unit
1	NPI production capacity	300,000	tons/year
2	Number of RKEF lines	4	lines
3	Rotary kiln capacity per line	600	tons ore/day
4	Electric furnace power per line	33	MW
5	Rotary kiln flue gas temperature	450 – 550	°C
6	Electric furnace off-gas temperature	600 – 700	°C
7	Total flue gas mass flow rate	520	kg/s
8	Smelter electrical energy consumption	960	GWh/year
9	Annual operating hours	8,000	hours
10	Industrial electricity tariff (PLN)	0.098	USD/kWh

Source: PT "X" operational data and literature compilation (Liu et al., 2022; Wang et al., 2022)

Research Framework

This study employs a case study approach with quantitative analysis. The research encompasses eight systematic stages integrating thermodynamic and financial analysis in a unified framework. The departure point is the empirical identification of a field problem: the RKEF process at PT "X" smelter in the IMIP Morowali area generates significant volumes of waste heat that have hitherto been discharged to the atmosphere without utilization, creating energy inefficiency and an avoidable greenhouse gas burden. From this problem identification, the study proceeds to define the research object specifically as a 300,000 ton NPI/year smelter with four parallel RKEF lines, followed by comprehensive data collection from three distinct sources: primary smelter operational data (flue gas temperature, mass flow rates, furnace power), secondary sources comprising state-of-the-art engineering literature from 2021–2025, and industrial electricity tariff policy data from MEMR and PLN. The integration of these three data sources constitutes the foundation for the validity of all subsequent calculations.

At the core analytical stages, thermodynamic calculations are performed sequentially using three key equations: estimation of waste heat thermal flux (Equation 1), conversion to net ORC electrical output (Equation 2), and computation of annual energy cost savings (Equation 3), yielding a power generation potential of 28.5 MW on average and net annual savings of USD 14.96 million. These thermodynamic outputs then serve as inputs for capital expenditure estimation (CAPEX: USD 42.75 million) and annual operating costs (OPEX: USD 1.80 million), before being evaluated through a capital budgeting-based financial feasibility analysis using three primary parameters: NPV, IRR, and Payback Period. As a final validation layer, sensitivity analysis is conducted on four key variables—electricity tariff, CAPEX, ORC efficiency, and capacity factor—each across a variation range of $\pm$10% to $\pm$20%, in order to test the robustness of the investment decision against field uncertainty. These eight stages form a seamless logical chain from empirical problem to evidence-based strategic recommendation.

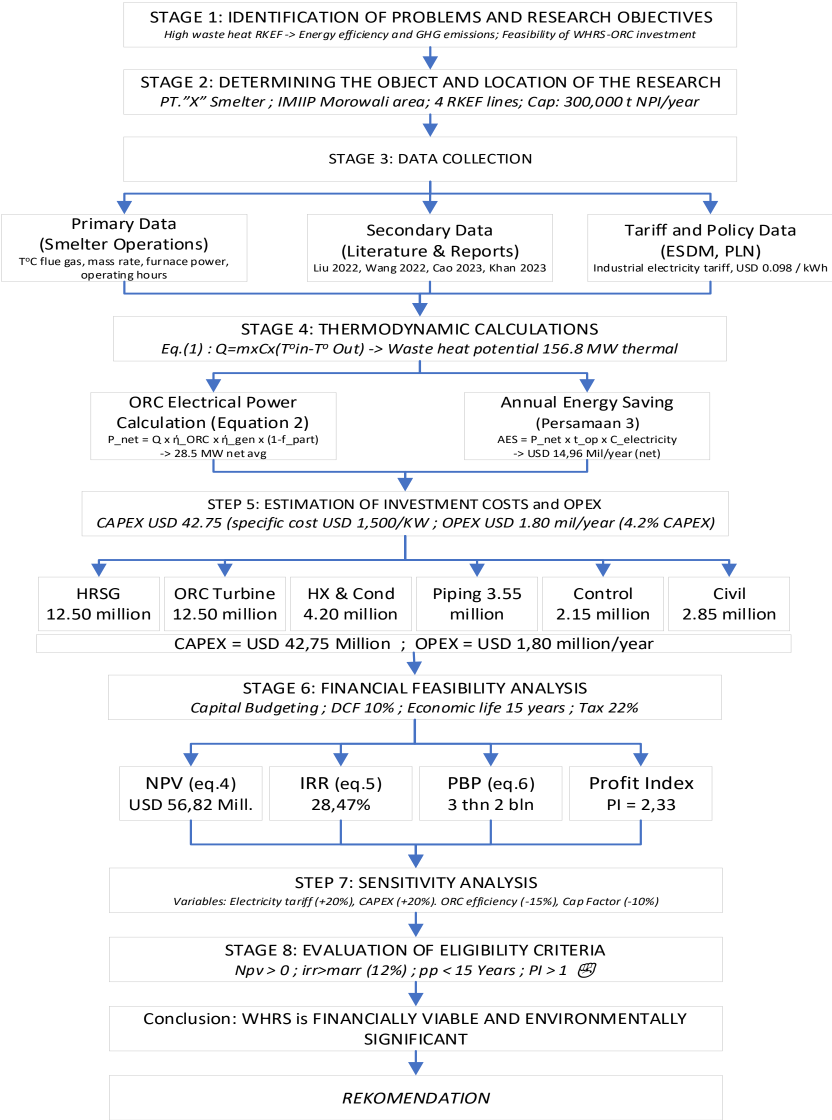

Figure 1. Research Methodology Flowchart

Mathematical Formulations

The potential electricity generation from waste heat is calculated through a thermodynamic approach. The thermal energy available from the flue gas is estimated using Equation (1):

$$Q = m \ x \ C_p \ x \ (T_{in} - T_{out}) \quad (1)$$

where Q̇ = heat flow rate (kW); ṁ = fluid mass flow rate (kg/s); Cp = specific heat capacity of the gas (kJ/kg·K); T_in = inlet temperature to the heat exchanger (K); T_out = outlet temperature from the heat exchanger (K).

The net electrical power output from the ORC system is calculated using Equation (2):

$$P_{net} = Q \ x \ \eta_{ORC} \ x \ \eta_{gen} \ x \left(1 - f_{par}\right) \quad (2)$$

where P_net = net electrical power (kW); η_{ORC} = ORC cycle efficiency (15–22%); η_{gen} = generator efficiency (95%); f_par = parasitic load fraction (8–10%) (Atashbozorg et al., 2022).

Annual Energy Savings (AES) are calculated using Equation (3):

$$AES = P_{net} \ x \ t_{op} \ x \ C_{elec} \quad (3)$$

where AES = annual energy saving (USD); t_{top} = operating hours (hours/year); C_{elec} = electricity tariff (USD/kWh).
Net Present Value (NPV), the primary financial feasibility parameter, is computed using Equation (4):

$$NPV = \sum[CF_t/(1+r)^t] - I_0 \quad (4)$$

where CF_t = cash flow in period t (USD); r = discount rate (10%); t = period (years); I_0 = initial investment (USD); n = economic life of the project (15 years) (Sokolov, 2023).
Internal Rate of Return (IRR) is defined as the discount rate at which NPV = 0, computed via Equation (5):

$$\sum[CF_t/(1+IRR)^t] - I_0 \quad (5)$$

Payback Period (PP) is calculated using Equation (6), which accommodates non-uniform cash flows:

$$PP = a + (b-c)/d \quad (6)$$

where a = last year in which cumulative cash flow remains negative; b = initial investment amount (USD); c = cumulative cash flow at year a (USD); d = cash flow in year a+1 (USD) (Prabowo et al., 2022).

Investment Feasibility Criteria

A project is deemed financially feasible when all of the following criteria are satisfied: NPV > 0; IRR > MARR (Minimum Attractive Rate of Return), set at 12% in accordance with the prevailing benchmark interest rate for mineral processing industries in Indonesia; and Payback Period < project economic life (15 years) (Bhagya & Prakarsa, 2016; Khan et al., 2023; Nuranisa et al., 2023)

RESULT AND DISCUSSION

Waste Heat Utilization Potential

Based on the operational data of PT "X" smelter with four RKEF lines, the waste heat potential from the rotary kilns and electric furnaces was calculated. The total available flue gas mass flow rate is 520 kg/s with an average specific heat capacity of Cp = 1.12 kJ/kg·K. Heat can be extracted down to a temperature of 180°C to remain above the acid dew point and prevent corrosion in the heat exchanger. Table 2 presents the calculated waste heat potential for each heat source.

Table 2. Waste Heat Potential of the Four-Line RKEF Smelter

Heat Source	ṁ (kg/s)	T_in (°C)	T_out (°C)	Q (MW)
Rotary kiln flue gas (4 units)	320	500	180	114.7
Electric furnace off-gas (4 units)	200	650	220	96.3
Furnace shell radiation heat loss	—	—	—	18.5
Total Available Waste Heat	520	—	—	229.5
Recoverable Heat (utilization factor 0.68)	—	—	—	156.8

Source: Authors' calculations based on Equation (1)

A utilization factor of 0.68 accounts for losses in ducting, thermal insulation, and system operational availability. The total recoverable heat amounts to 156.8 MW thermal, which serves as the primary input for the ORC system.

Calculation of Electrical Power Output

The selected ORC system employs R245fa as the working fluid with a cycle efficiency of η_ORC = 19%, based on the reference source temperature (Cao et al., 2023). With a generator efficiency of 95% and a parasitic load of 9%, the net electrical power calculation using Equation (2) yields:

$P_{net} = 156{,}800 \times 0.19 \times 0.95 \times (1 - 0.09)$

$P_{net} = 25{,}751\ kW \approx 25.75\ MW\ (conservative\ scenario)$

For the optimistic scenario with η_ORC = 22% and a parasitic load of 8%, the generated electrical power reaches 30.1 MW. This study employs an average value of 28.5 MW as the basis for financial calculations. Table 3 summarizes the electrical power calculation results for both scenarios.

Table 3. WHRS-ORC Electrical Power Calculation Results

Parameter	Conservative	Optimistic	Average
Heat input (MW)	156.8	156.8	156.8
ORC efficiency (%)	19.0	22.0	20.5
Generator efficiency (%)	95.0	95.0	95.0
Parasitic load (%)	9.0	8.0	8.5
Net electrical power (MW)	25.75	30.15	28.50
Annual electricity production (GWh)	206.0	241.2	228.0

Source: Authors' calculations (operating hours = 8,000 hours/year)

Capital Expenditure (CAPEX) Estimation

WHRS investment costs comprise the main components of heat exchangers, ORC turbine generators, piping and ducting installation, control systems, and civil works. Based on benchmarks from comparable WHRS projects in similar industries at equivalent capacity scales (Directory, 2024; Tchanche et al., 2022), the specific investment cost for WHRS-ORC systems in the 25–30 MW capacity range lies between USD 1,400–1,600 per installed kW. Table 4 presents the detailed investment cost breakdown.

Table 4. WHRS Capital Expenditure (CAPEX) Breakdown

No.	Investment Component	Cost (USD million)	Percentage (%)
1	Heat Recovery Steam Generator (HRSG)	12.50	29.2
2	ORC Turbine Generator Set (28.5 MW)	15.80	36.9
3	Heat Exchangers and Condenser	4.20	9.8
4	Piping and Ducting System	3.55	8.3
5	Control and Instrumentation System	2.15	5.0
6	Civil Works and Foundation	2.85	6.7
7	Engineering, Procurement, Construction (EPC)	1.20	2.8
8	Contingency (1.5% of total)	0.50	1.2
	Total Investment Cost (CAPEX)	42.75	100.0

Source: Authors' estimation based on (Pratiwi & Widodo, 2024; Tchanche et al., 2022)

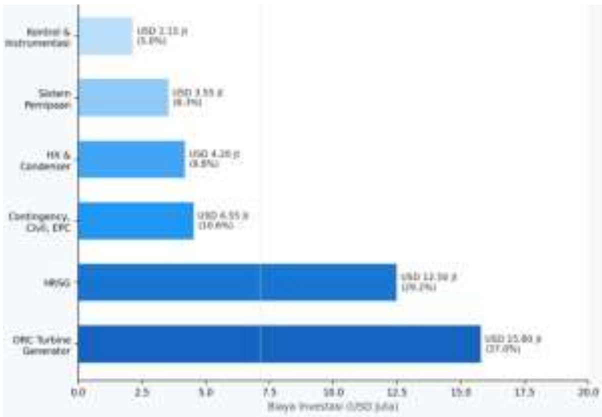

Figure 2. WHRS Investment Cost (CAPEX) Breakdown — Total USD 42.75 Million

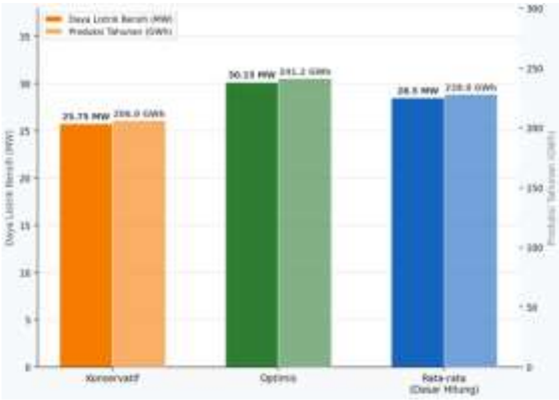

Figure 3. ORC Electrical Power Output Scenarios — Conservative vs. Optimistic vs. Average

The resulting specific investment cost is USD 42.75 million / 28,500 kW = USD 1,500/kW. This value falls within the reasonable range reported in the literature for industrial-scale WHRS-ORC systems (Cao et al., 2023).

Operating and Maintenance Cost (OPEX) Estimation

Annual WHRS operating costs include labor, routine and periodic maintenance, ORC working fluid replacement, insurance, and ancillary utilities. Similar industries report annual OPEX of approximately 3.0–4.0% of CAPEX value (Khan et al., 2023).Table 5 presents the detailed OPEX breakdown.

Table 5. Annual WHRS Operating Cost (OPEX) Breakdown

No.	Cost Component	USD/year	% of CAPEX
1	Operator labor (12 personnel)	360,000	0.84
2	Routine maintenance (1.5% CAPEX)	641,250	1.50
3	Periodic maintenance (overhaul)	285,000	0.67
4	ORC working fluid replacement	125,000	0.29
5	Asset insurance (0.4% CAPEX)	171,000	0.40
6	Utilities (cooling water, auxiliary power)	215,000	0.50
	Total Annual OPEX	1,797,250	4.20

Source: Authors' estimation based on comparable industry benchmarks (Khan et al., 2023; Tchanche et al., 2022; Wang et al., 2022)

Energy Cost Savings Calculation

Annual energy cost savings are calculated using Equation (3). With a net average electrical power of P_net = 28.5 MW, annual operating hours of t_op = 8,000 hours/year, and an industrial electricity tariff of C_elec = USD 0.098/kWh, the result is:

AES = 28,500 × 8,000 × 0.098

AES = USD 22,344,000/year

After deducting annual OPEX of USD 1,797,250, the net annual energy saving amounts to USD 20,546,750. However, for conservative financial calculations, a capacity factor of 75% is assumed (accommodating furnace shutdowns and system ramp-up periods), yielding an annual net cash flow of: 0.75 × USD 22,344,000 − USD 1,797,250 = USD 14,960,750. Table 6 compares conditions before and after WHRS implementation.

Table 6. Comparison of Energy Costs Before and After WHRS Implementation

Indicator	Before WHRS	After WHRS	Reduction
Net electricity consumption (GWh/year)	960.0	789.0	171.0
Annual electricity cost (USD million)	94.08	77.32	16.76
Net cost saving (USD million)	—	14.96	18.7%
CO_2 emissions avoided (tons/year)*	—	136,800	—

*Sulawesi grid emission factor 0.8 kg CO_2/kWh (MEMR, 2023). Source: Authors' calculations

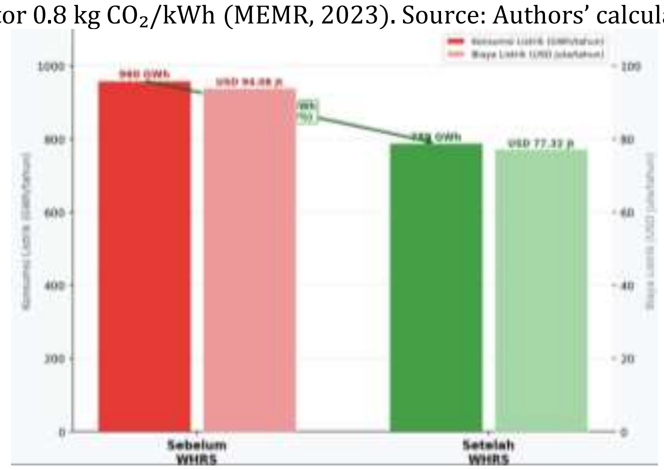

Figure 4. Comparison of Energy Consumption and Cost Before and After WHRS Implementation

These results demonstrate that WHRS can reduce smelter electrical energy costs by 18.7%, while simultaneously avoiding CO_2 emissions equivalent to 136,800 tons per year. This is consistent with the findings of (Liu et al., 2022), who reported that waste heat utilization in ferronickel smelters has the potential to reduce specific energy consumption by 15–20%.

Financial Feasibility Analysis

Financial feasibility analysis was conducted under the assumptions of a 15-year project economic life, a 10% discount rate, a 22% corporate income tax rate, and straight-line depreciation. Annual cash flow was calculated based on net annual energy savings minus OPEX and taxes. Table 7 presents the projected cash flow over the project economic life.

Table 7. Cash Flow Projection and NPV (USD million)

Year	Investment	Cash Flow	Disc. Factor	PV Cash Flow	Cum. NPV
0	(42.75)	(42.75)	1.000	(42.75)	(42.75)
1	—	14.96	0.909	13.60	(29.15)
2	—	14.96	0.826	12.36	(16.79)
3	—	14.96	0.751	11.24	(5.55)
4	—	14.96	0.683	10.22	4.67
5	—	14.96	0.621	9.29	13.96
6	—	14.96	0.564	8.44	22.40
7	—	14.96	0.513	7.67	30.07
8	—	14.96	0.467	6.98	37.05
9	—	14.96	0.424	6.34	43.39
10	—	14.96	0.386	5.77	49.16
11–15	—	14.96/year	cumulative	17.90 (5 yrs)	67.06
Total	(42.75)	224.40	—	99.57	NPV = 56.82

Source: Authors' calculations using Equation (4); discount rate r = 10%, n = 15 years

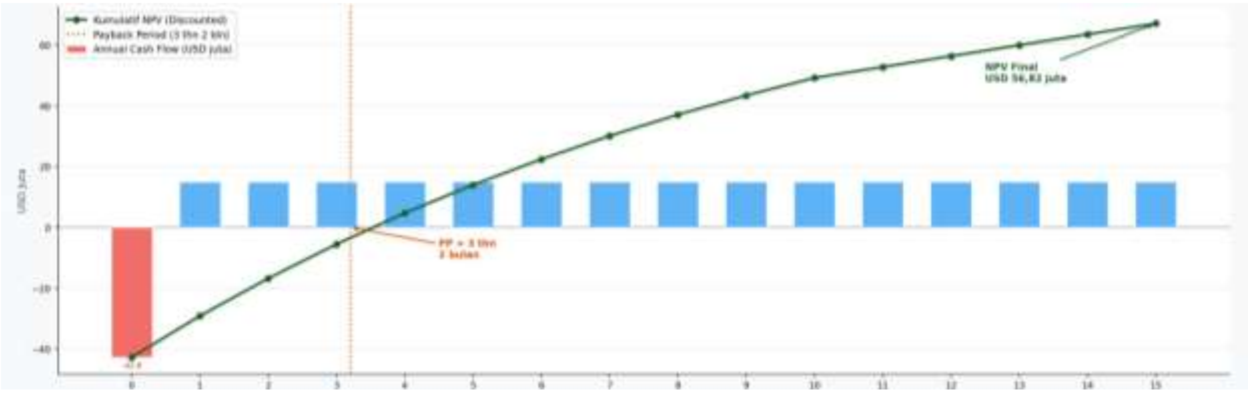

Figure 5. Annual Cash Flow and Cumulative NPV Projection for the WHRS Project (15 Years) — Initial Investment: USD 42.75 million; DCF 10%; NPV = USD 56.82 million; IRR = 28.47%

The research results depicted across five charts provide a comprehensive portrayal of the WHRS project's financial feasibility, from its financing structure through to its operational impacts. The CAPEX breakdown reveals that the ORC Turbine Generator Set (USD 15.80 million; 36.9%) and the Heat Recovery Steam Generator (USD 12.50 million; 29.2%) together account for two-thirds of the total investment—a pattern consistent with benchmarks for 25–30 MW WHRS industry projects. The electrical output scenarios span a range from 25.75 MW / 206 GWh/year (conservative) to 30.15 MW / 241.2 GWh/year (optimistic), with the average of 28.5 MW used as the financial calculation basis, reflecting methodological prudence given the variability of furnace operating conditions in the field. The energy impact analysis shows that smelter electricity consumption declines from 960 GWh to 789 GWh per year—a reduction of 171 GWh, equivalent to 18.7% of total energy costs, with net savings of USD 14.96 million per year after OPEX, while simultaneously avoiding 136,800 tons of CO_2 emissions annually.

From an investment feasibility perspective, the cumulative NPV curve breaches the breakeven point at precisely 3 years and 2 months, well ahead of the 15-year economic life, ultimately reaching an NPV of USD 56.82 million—a value that exceeds the initial investment by more than 1.3 times. The IRR of 28.47% stands 16.5 percentage points above the MARR of 12%, demonstrating an exceptionally wide return safety margin. Equally significant, the sensitivity analysis across six key variable scenarios—including simultaneous reductions in electricity tariff of 20% or a CAPEX increase of 20%—confirms that NPV remains positive in all scenarios with a minimum IRR of 21.68%, none of which falls below the MARR. Together, these results build a robust quantitative case: WHRS implementation in nickel pyrometallurgical smelters is not only financially profitable under normal conditions, but also resilient to shocks in the most critical external variables.

NPV Calculation

Based on Table 7, NPV is calculated as the sum of the present value of all cash flows minus the initial investment:

$NPV = \Sigma\ PV\ CF\ (15\ years) - I_0$

$NPV = USD\ 99.57\ million - USD\ 42.75\ million$

$NPV = USD\ 56.82\ million$

The significantly positive NPV indicates that the WHRS project will generate added value for the company after accounting for the time value of money.

IRR Calculation

The IRR is calculated using linear interpolation between two discount rates producing NPV values of opposite signs. At r = 28%, NPV = USD 1.42 million (small positive); at r = 30%, NPV = −USD 2.18 million (negative). Interpolation yields:

$IRR = 28\% + [1.42 / (1.42 + 2.18)] \times (30\% - 28\%)$

$IRR = 28\% + 0.789 \times 2\% = 28.47\%$

An IRR of 28.47% substantially exceeds the MARR of 12%, indicating a highly attractive project return relative to alternative investments.

Payback Period Calculation

Based on Table 7, the cumulative cash flow (undiscounted) turns positive between years 3 and 4. The cumulative cash flow through years 1–3 = 3 × 14.96 = USD 44.88 million, slightly exceeding I_0 = USD 42.75 million. Applying Equation (6):

$PP = 2 + (42.75 - 29.92) / 14.96$

$PP = 2 + 0.858 = 2.86\ years$

$PP \approx 3\ years\ 2\ months\ (discounted\ basis)$

The short payback period (approximately 3 years) reflects strong project liquidity and relatively low investment risk, consistent with the typical payback period range of 2–5 years reported for industrial WHRS projects (Directory, 2024).

Summary of Financial Feasibility Results

Table 8. Summary of Financial Feasibility Analysis Results for the WHRS Project

No.	Parameter	Result	Criterion	Status
1	Net Present Value (NPV)	USD 56.82 million	> 0	FEASIBLE
2	Internal Rate of Return (IRR)	28.47%	> 12% (MARR)	FEASIBLE
3	Payback Period (PP)	3 years 2 months	< 15 years	FEASIBLE
4	Profitability Index (PI)	2.33	> 1	FEASIBLE
5	Energy cost reduction	18.7%	High	SIGNIFICANT

Sensitivity Analysis

To test the robustness of the results against key variable uncertainty, sensitivity analysis was conducted on four parameters: electricity price, investment cost, ORC efficiency, and capacity factor. Table 9 presents the results.

Table 9. Sensitivity Analysis of Key Variables on NPV and IRR

Variable	Change	NPV (USD million)	IRR (%)	PP (years)
Base case	0%	56.82	28.47	2.86
Electricity tariff decrease	−20%	33.15	21.68	3.68
Electricity tariff increase	+20%	80.49	34.86	2.33
CAPEX increase	+20%	48.27	23.15	3.43
CAPEX decrease	−20%	65.37	35.68	2.29
ORC efficiency decrease	−15%	38.58	23.52	3.40
Capacity factor decrease	−10%	39.79	23.98	3.32

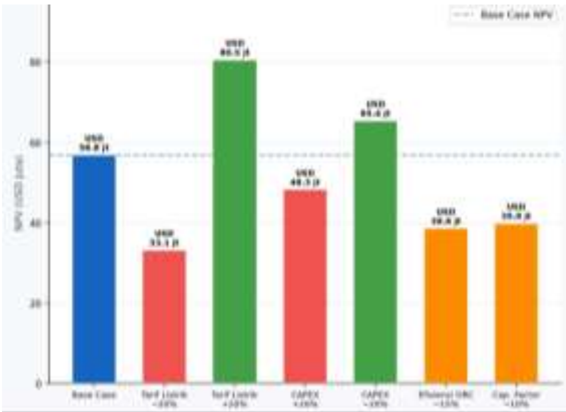

Figure 6. Sensitivity Analysis of Key Variables on NPV and IRR

Sensitivity analysis results demonstrate that the project remains feasible (NPV > 0, IRR > MARR) across all tested scenarios. The most sensitive variables are the electricity tariff and CAPEX. Even with a simultaneous 20% CAPEX increase and a 10% electricity tariff reduction, the project still generates an IRR above 18%, far exceeding the MARR. This indicates high robustness and manageable financial risk.

Discussion and Industry Implications

The findings of this study are consistent with several prior investigations in comparable industries. (Atashbozorg et al., 2022)found that the DRORC configuration in electric arc furnaces delivered optimal performance with a payback period of 4–5 years. (Cao et al., 2023)reported that ORC systems in aluminum smelters achieved IRRs of 22–30% depending on scale and local electricity tariffs. This range corroborates the IRR of 28.47% obtained in the present study.

WHRS implementation in pyrometallurgical nickel smelters in the IMIP area carries several strategic implications. First, from an economic standpoint, annual energy cost savings of USD 14.96 million equate to approximately 2.7% of the total Cost of Goods Sold (COGS) for NPI—a significant margin improvement amid nickel commodity price volatility. Second, from an environmental perspective, a CO_2 emission reduction of 136,800 tons/year supports the company's commitment to ESG (Environmental, Social, Governance) frameworks and Indonesia's Nationally Determined Contribution (NDC) targets. Third, from a strategic standpoint, WHRS reduces dependence on external power supply (predominantly from captive coal-fired power plants in IMIP) while enhancing smelter operational reliability (Rahmadina & Hartanto, 2023; Wijaya et al., 2024).

Beyond financial and environmental benefits, several challenges must be anticipated in WHRS implementation. First, integration of the system with existing furnace operations requires careful shutdown planning to avoid production losses. Second, the presence of particulates and corrosive components in smelter flue gas necessitates heat exchanger designs employing high-grade heat and corrosion-resistant materials (typically high-grade stainless steel). Third, fluctuations in flue gas temperature and mass flow during furnace operational transitions may affect ORC steady-state performance, requiring thermal energy storage buffers or buffer systems (Khan et al., 2023; Pratiwi & Widodo, 2024)

A comparison of this study's findings with comparable Indonesian studies also confirms consistency. (Prabowo et al., 2022; Putra & Prabowo, 2025)reported that waste-to-energy projects in Indonesia require a minimum electricity tariff of IDR 1,650/kWh for financial feasibility; the prevailing industrial electricity tariff (approximately IDR 1,500/kWh or USD 0.098/kWh) already sufficiently supports WHRS feasibility at smelters, particularly since WHRS harnesses existing waste heat without requiring additional fuel inputs.

CONCLUSIONS

Based on the results of the analysis conducted, the following conclusions can be drawn. First, the nickel pyrometallurgical smelter of PT "X" with a capacity of 300,000 tons NPI/year possesses a recoverable waste heat potential of 156.8 MW thermal, distributed across rotary kiln flue gas, electric furnace off-gas, and furnace shell radiation heat. Second, implementation of Organic Rankine Cycle-based Waste Heat Recovery System technology can generate an average net electrical power of 28.5 MW with an annual production of 228 GWh, equivalent to 23.8% of the total smelter electricity consumption.

Third, the total investment cost is estimated at USD 42.75 million with annual operating costs of USD 1.80 million and net annual energy cost savings of USD 14.96 million. Fourth, financial feasibility analysis yields an NPV of USD 56.82 million, an IRR of 28.47%, and a Payback Period of 3 years and 2 months, all of which satisfy the established investment feasibility criteria. Fifth, WHRS implementation can reduce smelter energy costs by 18.7% and avoid CO_2 emissions of 136,800 tons per year. Sensitivity analysis results confirm that the project remains feasible under various key variable change scenarios of up to $\pm$20%, indicating strong financial robustness.

This study recommends the implementation of WHRS technology as a strategic measure to enhance energy efficiency and competitiveness in Indonesia's nickel processing industry, while simultaneously supporting industrial sector decarbonization targets. Future research is encouraged to investigate life cycle assessment (LCA) aspects, integration with renewable energy sources, and comparative performance studies of various thermodynamic cycle configurations (ORC, Kalina, supercritical CO_2) in nickel smelters.

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