


Financial Feasibility Study for Utilizing Flue Gas Emissions from the Adipala Power Plant to Generate 5 kW of Electricity

Rendi Hendra Eka Hermawan¹, Eri Prabowo²

^{1,2}Program Studi Magister Teknik Elektro Institut Teknologi PLN, Jakarta, Indonesia

Article Info	ABSTRACT
<p>Keywords: Waste heat utilization Adipala PLTU Feasibility study Micro ORC.</p>	<p>Electric power reliability remains central to Indonesia's economic stability while decarbonization pressures increase. This study evaluates the technical and economic feasibility of recovering flue-gas heat from the Adipala coal-fired power plant to generate 5 kW via a micro Organic Rankine Cycle (ORC). Field measurements at the economizer duct show a flue-gas mass flow of 55,000 kg h⁻¹ at 170 °C, corresponding to about 400 kW_{th} of recoverable heat. A thermodynamic model with realistic parasitic losses and a 12% cycle efficiency indicates a net electrical output of 5 kW with exhaust temperature maintained at 110 °C and boiler backpressure limited to 2 mbar, so boiler operation is not disturbed. Economic appraisal uses a discounted cash-flow model with CAPEX USD 15,000, annual O&M USD 450, availability factor 0.80, electricity price USD 0.10 kWh⁻¹, and discount rate 10%. Results show annual net cash inflow USD 3,054, NPV ≈ USD 11,000, IRR ≈ 19.8%, BCR = 1.59, and a simple payback of ~4.9 years. Sensitivity checks indicate project resilience to reasonable variations in availability, carbon pricing, and component cost. The findings demonstrate that small-scale ORC deployment on plant economizers can be technically sound, economically attractive, and supportive of modest emissions reduction and asset-management goals for thermal power stations.</p>
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INTRODUCTION

The background of this research is rooted in the dynamics of national energy policy, which increasingly emphasize the acceleration of decarbonization without compromising the reliability of electricity supply. An official statement by the Ministry of Energy and Mineral Resources in August 2024 announced an early retirement plan for thirteen coal-fired power plants owned by PLN, including several relatively young units. This policy was adopted to reduce greenhouse gas emissions in accordance with Presidential Regulation No. 112 of 2022 concerning the acceleration of renewable energy development (Ahsan et al., 2023; Kementerian Energi dan Sumber Daya Mineral Republik Indonesia, 2024; Ramadhan & Prabowo, 2020). Nevertheless, the government asserted that any decision to cease operations must take into account the technical lifespan, efficiency, and reserve margin to ensure the stability of the Jawa Bali power system remains uncompromised.

Since August 2024, the Government of Indonesia has declared an early retirement plan for a number of coal-fired power plants, including the Adipala Power Plant, but required each

unit to present concrete emission reduction efforts while maintaining the reliability of power supply (Kementerian Energi dan Sumber Daya Mineral Republik Indonesia, 2024). At the same time, thermodynamic studies have demonstrated that flue gases with temperatures ranging from 130 to 150 °C emitted from the chimneys of coal power plants contain thermal energy that can be converted through the Organic Rankine Cycle (ORC) into micro-scale electricity generation of several kilowatts with an efficiency of 8–12 percent (Desmon Nababan & Prabowo, 2020; Kersatyo & Prabowo, 2020; Mahardika, 2025; Permana & Mahardika, 2019). Institutional support has become increasingly tangible since Exergy International and PT PLN Indonesia Power signed a cooperation agreement to conduct feasibility studies on waste heat utilization across power plants in Indonesia, paving the way for small-scale ORC technology suitable for 5 kW demonstration projects (Exergy, 2024). On the environmental front, the detection of lead contamination in rice samples from Cilacap has prompted public demands for stricter emission management at coal-fired power plants, including the utilization of waste heat to mitigate secondary pollution (Pandiangan & Audah, 2022; Prabowo et al., 2018; Simanjuntak & Prabowo, 2018). These four concurrent developments collectively create a strategic opportunity for the Adipala Power Plant to convert part of its flue gas emissions into 5 kW of electricity, thereby reducing carbon intensity, minimizing health risks, and supporting the national energy transition agenda in a gradual yet measurable manner.

Amidst these policy dynamics, the 660 MW Adipala Power Plant occupies a strategic position. The facility began commercial operation in March 2015 using supercritical technology designed for a 30-year lifecycle (Global Energy Monitor, 2025; Adi & Prabowo, 2023). Consequently, the unit still has a remaining design life of more than fifteen years. During its first decade of operation, the Adipala plant has continuously released high-temperature flue gas directly into the atmosphere through its chimney. This condition presents an opportunity to utilize the waste heat to generate additional electricity through a micro-generation system of five kilowatts, which can be installed without interfering with the primary combustion process.

International studies on waste-heat recovery have shown that small-scale Organic Rankine Cycle (micro-ORC) technology can convert residual thermal energy at medium temperatures into electricity with thermal efficiencies ranging from 8 to 12 percent (International Energy Agency, 2022). Such conversion not only reduces the carbon intensity per kilowatt-hour but also improves the capacity factor, as part of the plant's internal power demand such as lighting and control systems can be met by the micro-generator. Comparable feasibility studies in Indonesia have proven that micro-ORC systems below 50 kW in coal-fired power plants can yield positive net present values and payback periods of less than seven years when carbon pricing is monetized (Adli et al., 2025).

Although the technological potential appears promising, no existing research has specifically analyzed the technical and economic feasibility of utilizing flue gas emissions at the Adipala Power Plant to drive a five-kilowatt generator. The air-injection characteristics, air-to-fuel ratio, flue-gas temperature, and operational-load variations at Adipala differ from those of older power plants, making it impossible to directly apply simulation outcomes or

case-study results from other facilities. Furthermore, integrating a micro-ORC system requires detailed assessments of heat dissipation, boiler-pressure stability, and potential changes in maintenance patterns. Without a comprehensive feasibility assessment, any investment decision could pose both technical and financial risks to operators and policymakers.

This research aims to evaluate technical feasibility through thermodynamic characterization of flue gas, system design of energy conversion, and operational compatibility analysis. Simultaneously, it will assess economic feasibility by estimating capital costs, operation and maintenance expenditures, projected savings in parasitic energy consumption, and the monetization of carbon-emission reductions. The resulting findings are expected to provide a scientific basis for policymakers in formulating more adaptive early-retirement strategies, for operators in evaluating asset-management options, and for the public in securing access to cleaner and more reliable electricity supply.

METHODS

This study employed a quantitative descriptive approach. Primary and secondary data were collected systematically to assess both technical and economic feasibility, encompassing the determination of technical parameters, capacity calculations, and project economic evaluation. The object of analysis was the utilization of waste heat from the economizer duct of the Adipala coal-fired power plant for electricity generation via a micro-scale Organic Rankine Cycle (ORC); ORC technology is widely recognized as an effective option for converting low- to medium-temperature residual heat into electrical energy, and small-scale (micro) ORC implementations have been demonstrated in experimental and field studies (Bianchi, 2017; Mahmoudi, 2018; Wang et al., 2012). Field measurements on the economizer duct recorded a flue-gas mass flow rate of 55,000 kg·h⁻¹ at 170 °C, with a minimum allowable exhaust temperature of 110 °C to prevent corrosion and a back-pressure limit of approximately 2 mbar so as not to interfere with boiler operation; recovering heat from economizer or pre-treatment locations has been shown feasible under similar flue-gas conditions in utility applications (Carcasci, 2014; Smith et al., 2016). These parameters served as operational constraints in the system design and simulations.

Primary data were obtained from the Distributed Control System (DCS), which logs real-time pressure, steam flow, temperature, and turbine load; these data were exported as historical records for trend analysis. The accuracy of primary data was verified against the Continuous Emission Monitoring System (CEMS) connected to the environmental regulator, such that discrepancies in flue-gas concentrations could be used as indicators of sensor error approaches for integrating and cross-validating DCS and CEMS datasets and for developing model-based emission monitoring systems are established in the literature (Garcia & Brown, 2015; Lee & Kim, 2019). Secondary data included ASME PTC 4.1 and ASME PTC 46 standards as references for testing and performance calculations, as well as planning and regulatory documents such as the RUPTL for load and tariff assumptions. Official PLN reports were used as external comparators for capacity factors, network losses, electricity sale prices, fuel cost structure, and operational loads.

Internal validity was maintained through triangulation, namely by matching peak-hour turbine loads with shift logs, aligning monthly coal consumption from the fuel yard with daily DCS aggregates to avoid stock bias, and confirming tariffs and load projections based on the latest RUPTL and market information (Johnson et al., 2013). External validity was assessed by comparing outputs from the DCS and CEMS with PLN's official statistics. Emission and safety provisions from Minister of Environment and Forestry Regulation No. 15 of 2019 and Minister of Energy and Mineral Resources Regulation No. 11 of 2021 were employed as references to ensure that technical parameters and monitoring complied with legal limits.

The technical analysis commenced with quantification of recoverable enthalpy derived from the temperature difference between the flue gas and the safe exhaust temperature limit. Cycle efficiency and parasitic/supporting losses were incorporated to obtain a realistic estimate of net power; the thermodynamic modelling and configuration selection follow established approaches for micro- and small-scale ORC systems targeting medium-temperature heat sources (Bianchi & Cocco, 2016; Petrovic et al., 2018). ORC configuration selection targeted the medium-temperature range compatible with the economizer temperature. This step followed the thermodynamic modelling framework described in the manuscript.

Financial feasibility was evaluated using a discounted cash-flow model. Calculated indicators included Net Present Value (NPV), Internal Rate of Return (IRR), Benefit–Cost Ratio (BCR), and Payback Period, with definitions and acceptance criteria as formulated in the theoretical framework (Damodaran, 2012). Economic parameters such as analysis horizon, discount rate, CAPEX, O&M, and assumed electricity sale price were set based on official secondary data and industry practice, then coupled with the technical analysis results to compute annual net cash flows. Result robustness was tested through sensitivity analyses varying availability factors, carbon price, and changes in major component costs. These scenarios demonstrated whether NPV, IRR, and BCR remained within acceptable feasibility zones when key variables shifted within ranges reasonable for power-plant operation (Hammond & Jones, 2011).

RESULTS AND DISCUSSION

PT. Indonesia Power UJP PLTU Jawa Tengah 2 Adipala

The company serving as the object of this study is PT Indonesia Power UJP PLTU Jawa Tengah 2 Adipala, which commenced commercial operation in 2016. This enterprise is wholly owned by PT Indonesia Power and is located on Jalan Laut, Bunton Village, Adipala Subdistrict, Cilacap Regency, Central Java, occupying an industrial site of approximately 52 hectares. Its principal product is electric energy, with a single unit nameplate output capacity of 660 MW. Electricity produced by this plant is transmitted via the JAMALI (Java–Madura–Bali) transmission network. Coal is the primary fuel source. For communications, the company can be contacted at telephone number 0282 5259647.



Figure 1. PLTU Jawa Tengah 2 Adipala

PLTU Jawa Tengah 2 Adipala represents the most recent PPDE (coal-fired power generation) facility constructed on Java Island and is operated by PT Indonesia Power through the Jawa Tengah 2 Adipala Generation Service Unit (Unit Jasa Pembangkit). Distinct from other PPDE plants, this project implements a supercritical boiler achieving steam pressures of up to 25.4 MPa. The plant was developed to reinforce the energy supply for the Java–Madura–Bali power system, with interconnection to the 500 kV transmission network via the Kesugihan Cilacap Grid Substation. Similar to other PPDE units, PLTU Jawa Tengah 2 Adipala utilizes low-rank coal with a calorific value of approximately $4,200 \text{ kcal}\cdot\text{kg}^{-1}$ in line with governmental policy encouraging the exploitation of abundant domestic resources. The selection of this fuel is also aimed at reducing fuel-oil usage, whose production costs are substantially higher. Therefore, this plant not only supports the reliability of the JAMALI system but also offers operational cost efficiencies compared with oil-fired generation.

Technical Data of Main Components of the Adipala Power Plant

The boiler utilized at PLTU Jawa Tengah 2 Adipala was manufactured by Babcock & Wilcox Beijing and is of the Supercritical Separator Wall Firing type. This boiler is capable of producing dry steam at a rate of 2,069 tons per hour, with a superheater steam pressure of 25.4 MPa at 571 °C and a reheated steam pressure of 4.51 MPa at 569 °C. Coal serves as the primary fuel, while high-speed diesel (HSD) is used for initial ignition. The installed prime mover is a Shanghai Electric China N660-24.2/566/566 model steam turbine with a rated capacity of 660 MW. Superheated steam enters the high-pressure stage at 24.2 MPa and 566 °C, is reheated at 4.15 MPa and 566 °C, and then proceeds to the intermediate-pressure section. Operating at a rotational speed of 3,000 rpm, the turbine comprises three expansion stages, consisting of 12 high-pressure (HP) blades, 8 intermediate-pressure (IP) blades, and two sets of 7 low-pressure (LP) blades each.

The generator alternator, also manufactured by Shanghai Electric China, operates at 3,000 rpm and delivers an output voltage of 22 kV, a current of 20,377 A, and an apparent power of 776.5 MVA at a power factor of 0.85 lagging. The stator winding is cooled using pressurized hydrogen gas at 0.45 MPa. The pulverizer, model YMKQ630-6-6.3 produced by Beijing Power Equipment Group, grinds coal to a fineness of 200 mesh at a throughput of 73,800 kg per hour with a feed moisture of 23.6 %. Its prime mover is a 900 kW, 6 kV, 100 A, 50 Hz motor operating at 28.6 rpm.

The Boiler Feedwater Pump Turbine (BFPT) system consists of a multistage centrifugal pump, model HPT300-340IIM-6S, manufactured by Shanghai Power Equipment, driven by a steam turbine, model ND(Z)84/79/07, from Shanghai Turbine Co. Ltd. The pump delivers 1,232.72 m³/s of feedwater up to a head of 3,206.98 m at an efficiency of 82.82 %, while its drive turbine supplies 13.5 MW using both low-pressure and high-pressure steam at 1.154 MPa (390.9 °C) and 4.904 MPa (353.7 °C), operating at 2,800–6,000 rpm. The Forced Draft Fan (FDF), model GU15038-02, manufactured by Chengdu KK&K Power Fan Co. Ltd, delivers 217.4 m³/s of forced air at 5,318 Pa, driven by a 3,150 kW motor at 990 rpm. The Primary Air Fan (PAF), model GU24034-12, rated at 1,400 kW, provides 163.9 m³/s of airflow at 1,490 rpm. The Induced Draft Fan (IDF), model YA17436-8Z, handles 598.5 m³/s of flue gas at 4,540 Pa using a 3,600 kW motor at 595 rpm.

The Electrostatic Precipitator (ESP), produced by Zhijiang Jiahuan Electronic Co. Ltd, operates at a gas temperature of 133 °C, with an electrode voltage of 72 kV DC and current of 3 A, achieving a dust-collection efficiency of 99.5 %. The exhaust stack, standing 275 m high, is constructed of reinforced concrete with a base diameter of 30 m and a top diameter of 14 m, housing two flue-gas ducts each measuring 5.5 m in diameter. Flue gas enters the stack at 150 °C and flows upward at a velocity of 2 m/s.

The Circulating Water Pump, model 90LKXA-20.5 from China Hunan Xeme Changsa, circulates cooling water up to a head of 20.5 m with an NPSHr of 8.41 m, driven by a 12,430 kW, 6 kV, 50 Hz, three-phase motor. The step-up transformer, rated at 800 MVA, was manufactured by Boading Tianwei Baobian Electric Co. Ltd, featuring on-load tap-changing capability of $\pm 8 \times 1.2596$ % and dual copper windings, operating at 500 kV primary and 22 kV secondary, 50 Hz, three-phase, with primary currents of 802.8 / 21,073 A. The Booster Feedwater Pump (BFBP), a single-stage centrifugal model from Shanghai Power Equipment, delivers 1,137.98 t/h at a head of 142.5 m with 83.44 % efficiency, driven by a 590 kW motor at 1,490 rpm. The Condensate Extraction Pump (CEP), a multistage centrifugal unit from the same manufacturer, pumps 1,823 t/h at NPSHr = 4.4 m, with a motor power of 1,922 kW operating at 1,460 rpm.

Financial Analysis

a. Net Present Value (NPV)

The following data describe the financial parameters of the Adipala Cilacap coal-fired power plant with a capacity of 660 MW. All values are expressed in 2025 U.S. dollars.

Table 1. Adipala Cilacap Power Plant Data

Variable	Value	Unit	Brief Explanation
Net Installed Power	5	kW	Net output of the micro-ORC turbine after auxiliary load
Availability Factor	0.80	–	Flue gas available for approximately 7,000 hours per year
Annual Electricity Production	35,040	kWh	5 kW × 8,760 hours × 0.80
Electricity Selling Tariff	0.10	USD kWh ⁻¹	Assumed internal PLN selling price

Variable	Value	Unit	Brief Explanation
Annual Gross Revenue	3,504	USD	Production × Tariff
Fuel Cost	0	USD	Waste heat is free
Operation & Maintenance Cost	450	USD yr ⁻¹	3 percent of CAPEX
Initial Investment	15,000	USD	3,000 USD kW ⁻¹ × 5 kW
Economic Lifetime	20	years	Manufacturer's recommendation for ORC module
Discount Rate	10	percent	Standard for project evaluation in efficiency programs

The economic feasibility assessment commenced with the specification of the baseline variables and their conversion into a sequence of discounted cash flows over a twenty-year project horizon. Annual electricity output was derived from the net 5 kW ORC turbine capacity, assuming an availability factor of 80 percent; thus, the plant is expected to generate 35,040 kWh per year (5 kW × 8,760 hours × 0.80). Applying an internal selling tariff of USD 0.10 per kWh yields annual gross revenue of USD 3,504. Because the energy source is waste heat, no fuel costs are allocated. Operation and maintenance expenditures are assumed to equal 3 percent of the capital expenditure; for an initial investment of USD 15,000 this implies annual O&M of USD 450. Accordingly, the yearly net cash inflow from operations is USD 3,054 (gross revenue minus O&M).

Each annual net cash flow was discounted at a real discount rate of 10 percent. Discount factors decline from 0.909 in year one to 0.149 in year twenty, and each year's present value was computed by multiplying the annual net cash flow by the corresponding discount factor (for example, year three yields a present value of USD 2,294.52). The sum of these discounted net cash flows over the twenty-year horizon amounts to USD 26,000.42. Subtracting the initial capital outlay of USD 15,000 produces a Net Present Value (NPV) of USD 11,000.42, indicating a positive present-value surplus and a net enhancement of wealth under the assumptions used.

The Internal Rate of Return (IRR) was determined by solving for the discount rate that equates the present value of future net cash flows to the initial investment. Numerical solution methods (e.g., Newton–Raphson or spreadsheet IRR) give an IRR of approximately 19 percent, which substantially exceeds the 10 percent discount benchmark. A simple, undiscounted payback analysis shows cumulative nominal cash flows reach USD 12,216 after four years and USD 15,270 by the end of year five, indicating a payback point at roughly 4.9 years (rounded to five years). Collectively, the stable annual net cash flow of USD 3,054, positive NPV of about USD 11,000, IRR ≈ 19 percent, and sub-five-year payback support the conclusion that the 5 kW micro-ORC waste-heat recovery project is financially viable over a twenty-year horizon under the stated cost and tariff assumptions.

The boiler utilized at PLTU Jawa Tengah 2 Adipala was manufactured by Babcock & Wilcox Beijing and is of the Supercritical Separator Wall Firing type. This boiler is capable of producing dry steam at a rate of 2,069 tons per hour, with a superheater steam pressure of 25.4 MPa at 571 °C and a reheated steam pressure of 4.51 MPa at 569 °C. Coal serves as the

primary fuel, while high-speed diesel (HSD) is used for initial ignition. The installed prime mover is a Shanghai Electric China N660-24.2/566/566 model steam turbine with a rated capacity of 660 MW. Superheated steam enters the high-pressure stage at 24.2 MPa and 566 °C, is reheated at 4.15 MPa and 566 °C, and then proceeds to the intermediate-pressure section. Operating at a rotational speed of 3,000 rpm, the turbine comprises three expansion stages, consisting of 12 high-pressure (HP) blades, 8 intermediate-pressure (IP) blades, and two sets of 7 low-pressure (LP) blades each.

Table 2. Cash Flow Summary for the Adipala Power Plant

Year	Revenue (USD)	O&M (USD)	Net CF (USD)	Discount Factor	PV (USD)	Cumulative PV (USD)
0	0	0	-15,000	1.000	-	-15,000.00
					15,000.00	
1	3,504	450	3,054	0.909	2,776.36	-12,223.64
2	3,504	450	3,054	0.826	2,523.97	-9,699.68
3	3,504	450	3,054	0.751	2,294.52	-7,405.16
4	3,504	450	3,054	0.683	2,085.92	-5,319.24
5	3,504	450	3,054	0.621	1,896.29	-3,422.95
6	3,504	450	3,054	0.564	1,723.90	-1,699.05
7	3,504	450	3,054	0.513	1,567.18	-131.87
8	3,504	450	3,054	0.467	1,424.71	1,292.84
9	3,504	450	3,054	0.424	1,295.19	2,588.03
10	3,504	450	3,054	0.386	1,177.45	3,765.48
11	3,504	450	3,054	0.350	1,070.41	4,835.89
12	3,504	450	3,054	0.319	973.10	5,808.99
13	3,504	450	3,054	0.290	884.64	6,693.63
14	3,504	450	3,054	0.263	804.21	7,497.84
15	3,504	450	3,054	0.239	731.10	8,228.94
16	3,504	450	3,054	0.218	664.64	8,893.58
17	3,504	450	3,054	0.198	604.22	9,497.80
18	3,504	450	3,054	0.180	549.29	10,047.09
19	3,504	450	3,054	0.164	499.35	10,546.44
20	3,504	450	3,054	0.149	453.96	11,000.40

The calculations show that the 5 kW micro-ORC project generates an annual net cash flow of USD 3,054, which is derived from an annual gross revenue of USD 3,504 less annual O&M expenses of USD 450. Discounting these annual cash flows at a 10% rate produces discount factors that decline from 0.909 in year 1 to 0.149 in year 20, yielding a series of present values that begin at USD 2,776 in year 1 and fall to USD 454 in year 20; the cumulative sum of these discounted benefits equals USD 26,000. The initial capital outlay of USD 15,000 is recorded as a year-0 negative cash flow, and subtracting this investment from the discounted benefits produces an NPV of approximately USD 11,000 equivalent to a net wealth increase of more than 70% relative to the invested capital. Solving for the discount rate that sets NPV to zero yields an IRR of roughly 19%, i.e., nearly double the 10% cost-of-

capital benchmark. On an undiscounted basis, cumulative nominal cash flows reach USD 15,270 by the end of year five, giving a simple payback of about 4.9 years (rounded to five). Taken together, the stable annual net cash flow, positive NPV (~USD 11,000), IRR (~19%), and sub-five-year payback indicate that recovering waste heat at Adipala to produce 5 kW of electricity is financially viable over a twenty-year horizon under the stated cost and tariff assumptions.

b. Payback Period (PP)

Table 3. Payback Period Data for the Adipala Cilacap Power Plant

Item	Value (USD)	Source / Formula
Initial Investment (CAPEX)	15,000	ORC skid package 5 kW × 3,000 USD kW ⁻¹
Annual Gross Revenue	3,504	35,040 kWh × 0.10 USD kWh ⁻¹
Annual O&M Cost	450	3 % × 15,000
Annual Net Cash Flow	3,054	3,504 – 450

Table 4. Development of Cash Flows at Adipala Cilacap Power Plant

Year (t)	Net Cash Flow (USD)	Cumulative Cash Flow (USD)
1	3,054	3,054
2	3,054	6,108
3	3,054	9,162
4	3,054	12,216
5	3,054	15,270

The Payback Period (PP) calculation indicates that the initial capital investment of USD 15,000 will be recovered after four complete years and approximately nine months into the fifth year of project operation. The annual net cash inflow of USD 3,054 results from the difference between the annual gross revenue of USD 3,504 and the annual operation and maintenance cost of USD 450. After the first year, cumulative cash inflows reach USD 3,054; by the end of the second year, the total rises to USD 6,108; continuing linearly to USD 9,162 at the end of the third year and USD 12,216 by the end of the fourth. The unrecovered portion of the investment after four years is USD 2,784. Given that the annual net cash flow in the fifth year remains USD 3,054, the fraction of the fifth year required to close the remaining balance is calculated as $2,784 / 3,054 = 0.91$ years. Consequently, the simple payback period is 4.91 years, conventionally rounded to five years in financial reporting.

In practical terms, this means that the USD 15,000 micro-ORC investment can be fully repaid through savings and energy sales in less than half of the planned twenty-year economic lifetime. After the 4.91-year break-even point, all subsequent annual net revenues of USD 3,054 represent surplus cash that continues to accumulate as positive returns to the project until the end of its operating life.

c. Benefit–Cost Ratio (BCR)

Table 5. Key Parameters of the Adipala Cilacap Power Plant

Variable	Value	Unit	Remarks
Annual Electricity Production	35,040	kWh	5 kW × 8,760 h × 0.80

Variable	Value	Unit	Remarks
Electricity Selling Tariff	0.10	USD kWh ⁻¹	Internal tariff assumption
Annual Gross Revenue (Benefit)	3,504	USD	35,040 kWh × USD 0.10
Annual O&M Cost	450	USD	3 % of CAPEX
Initial Investment (CAPEX)	15,000	USD	3,000 USD kW ⁻¹ × 5 kW
Project Lifetime	20	years	Operational life of micro-ORC system
Discount Rate	10 %	–	PLN evaluation reference

The annual electricity production of 35,040 kWh is derived from the net design capacity of five kilowatts multiplied by 8,760 operating hours per year and an availability factor of eighty percent. The 5 kW capacity was selected because the available waste heat in the economizer duct of the Adipala coal-fired power plant at an average temperature of 170 °C is sufficient to drive a micro-organic turbine after accounting for auxiliary loads such as pumps, fans, and inverters. The 0.80 availability factor reflects the baseload operation pattern of the plant, which typically maintains loads above ninety percent for approximately seven thousand hours per year. When unit load decreases, the flue-gas temperature falls below 150 °C, at which point the ORC system automatically shuts down to prevent corrosion; hence, full availability (100 %) is not assumed.

The electricity selling tariff of USD 0.10 per kilowatt-hour corresponds to the 2025 tariff for medium-voltage commercial customers (category B2). Assuming that the generated power is supplied to the internal network or sold to PLN under a supplementary-supply arrangement, this price is considered conservative lower than household retail tariffs but higher than the export rate for rooftop solar surplus. The total investment cost of USD 15,000 is based on the market price of micro-ORC skid packages, averaging USD 3,000 per kilowatt. This amount includes a compact heat recovery steam generator, radial turbine, working-fluid pump, air-cooled condenser, control panel, and grid-tie inverter. The benchmark of USD 3,000 kW⁻¹ was derived from vendor surveys in Europe and China for 10–50 kW demonstration projects conducted in 2024, and is therefore relevant for the much smaller 5 kW capacity scale.

Annual operation and maintenance (O&M) costs are estimated at 3 percent of the capital expenditure, or USD 450 per year. This percentage covers the annual turbine service contract, lubricant replacement, heat-exchanger inspection, and condenser-fan maintenance. For micro-units without fuel consumption, O&M costs typically range from two to four percent of CAPEX, making three percent a reasonable midpoint assumption. The economic lifetime of twenty years aligns with the wear-curve characteristics of micro-radial turbines and aluminum plate-fin heat exchangers. Small-scale ORC manufacturers commonly offer five-year warranties and technical lifespans of up to twenty years, with a major overhaul scheduled in the tenth year; thus, the two-decade assumption is technically realistic. The residual value at the end of the project life is taken as zero to maintain conservative estimates.

The discount rate of ten percent reflects PLN's corporate cost of capital for small-scale energy-efficiency projects. This figure is slightly higher than the state-owned bank lending rate yet lower than the hurdle rate applied to large-scale generation projects, making it appropriate for a low-risk investment utilizing waste heat and requiring no fuel procurement. Under these assumptions, annual gross revenue is USD 3,504, annual O&M cost is USD 450, and annual net cash flow is USD 3,054. Discounting the twenty-year series of benefits and costs at the 10 percent rate results in a present value of benefits of USD 26,000 and a present value of costs of USD 18,831, yielding a Benefit–Cost Ratio (BCR) of 1.59. All baseline parameters were selected to represent the actual technical characteristics of the Adipala Power Plant, current market prices for micro-ORC equipment, and the prevailing tariff and discount-rate policies typically applied by Indonesian electric utilities.

Table 7. Results of BCR Calculation for the Adipala Cilacap Power Plant

Component	Value (USD)
Present Value of Benefits (\sum PV of Revenue)	29,868
Present Value of CAPEX	15,000
Present Value of O&M (\sum PV of Operating Costs)	3,831
Total Present Value of Costs	18,831
Benefit–Cost Ratio (BCR)	1.59

The Benefit–Cost Ratio (BCR) for the Adipala micro-ORC project reaches 1.59. This figure was obtained after discounting all annual gross revenues of USD 3,504 at a ten-percent discount rate over the twenty-year project lifetime, resulting in a total present value of benefits amounting to USD 29,868. On the cost side, the initial investment of USD 15,000 combined with the present value of operation and maintenance expenses of USD 3,831 yields a total present value of costs of USD 18,831. Dividing the present value of benefits by the total present value of costs produces a BCR of 1.59.

This ratio implies that every dollar of expenditure made today is projected to generate USD 1.59 in equivalent present-value benefits. Because the ratio exceeds unity, the project is considered economically efficient under the cost–benefit analysis framework. The excess of benefits over costs not only covers capital recovery and routine operating expenses but also provides a surplus margin, confirming that the utilization of waste heat for a five-kilowatt power generation unit at the Adipala plant is economically feasible under the assumed cost and tariff parameters.

d. Internal Rate of Return (IRR)

The computation of the Internal Rate of Return (IRR) began with assembling the series of net cash flows consisting of only two elements: the initial investment at year zero and the recurring annual positive cash inflows during the operational years.

Table 8. Basic Cash Flow Series of the Adipala Cilacap Power Plant

Variable	Value	Unit	Formula / Source
Initial Investment (CAPEX)	15,000	USD	ORC skid package 5 kW \times 3,000 USD kW ⁻¹
Annual Net Cash Flow (CF)	3,054	USD	Revenue 3,504 USD – O&M 450 USD

Variable	Value	Unit	Formula / Source
Analysis Horizon	20	years	Technical lifetime of the micro-ORC module
Discount Rate Tested	10–20	percent	Range for NPV root finding

The NPV function NPV(r) was evaluated at several discount rates to identify the interval where its sign changes from positive to negative. The results are summarized in the following table.

Table 9. NPV Values of the Adipala Cilacap Power Plant

Discount Rate (r)	NPV (USD)
10 %	11,000.42
15 %	4,116.00
18 %	1,347.29
19 %	578.03
19.80 %	8.27
19.90 %	-60.30
20 %	-128.30

The calculation results indicate that the Internal Rate of Return (IRR) of the micro-ORC project is approximately 19.8 percent. This value was obtained by solving the Net Present Value (NPV) equation in which the initial investment of USD 15,000 represents the year-zero cash outflow, followed by a uniform annual net cash inflow of USD 3,054 over twenty years. Testing across several discount rates revealed that NPV remains slightly positive at USD 8.27 for a 19.80 percent discount rate but becomes negative at -USD 60.30 when the rate reaches 19.90 percent. Linear interpolation within this narrow interval places the zero-NPV intersection at 19.81 percent. Substitution of this rate back into the present-value function yields a deviation approaching zero, validating the IRR value of 19.8 percent.

This result implies that the project's cash flow provides a return nearly twice the reference cost of capital of ten percent. Such a high IRR confirms that the positive NPV of USD 11,000 observed earlier is not coincidental but a direct consequence of the high ratio between net annual earnings and the relatively small capital investment. As long as the electricity selling tariff remains around USD 0.10 kWh⁻¹ and operating expenses do not exceed three percent of total investment, the profit margin remains broad. A simple sensitivity check shows that the IRR would decline to the ten-percent cost-of-capital threshold only if the annual net cash flow were to fall by nearly half either due to a drastic reduction in capacity factor or a doubling of maintenance costs. Such conditions are unlikely to occur without major disruptions to waste-heat supply or severe maintenance failures; therefore, the project can be considered financially robust.

From an academic standpoint, an IRR substantially higher than the Weighted Average Cost of Capital (WACC) satisfies the classical investment-theory criterion of financial feasibility: the project enhances shareholder value, provides a buffer against uncertainty, and delivers a payback period of less than five years. In summary, the conversion of flue-gas waste from the Adipala Power Plant into a 5 kW electricity output proves to be not only technically and environmentally sound but also highly attractive from an economic-return perspective.

Discussion

From a financial perspective, the five-kilowatt micro-ORC project utilizing flue-gas emissions from the Adipala Power Plant demonstrates a highly attractive return profile. The required initial investment amounts to only USD 15,000, corresponding to the market cost of an ORC skid package priced at approximately USD 3,000 per kilowatt. Revenue is generated through electricity sales of 35,040 kilowatt-hours per year at a conservative tariff of USD 0.10 per kilowatt-hour, resulting in an annual gross income of USD 3,504. Since waste heat incurs no fuel cost, the only recurring expense is operation and maintenance, estimated at three percent of capital expenditure, or USD 450 per year. The difference between these values yields an annual net cash flow of USD 3,054.

Assuming constant cash flows and a ten-percent discount rate, the twenty-year present-value annuity factor equals 8.513. This corresponds to a present value of benefits of USD 29,868, while the present value of total costs including the initial investment and discounted operating expenses amounts to USD 18,831. The difference between these two figures results in a positive Net Present Value (NPV) of approximately USD 11,000. The Internal Rate of Return (IRR), determined as the discount rate at which NPV equals zero, is found to be around 19.8 percent nearly double the reference cost of capital. This places the project not only within the “feasible” category but among those with a high-return profile. The cumulative undiscounted cash flow reaches full capital recovery by the fifth year, giving a payback period of approximately 4.9 years. The Benefit Cost Ratio (BCR) of 1.59 further confirms that each dollar invested today is projected to yield USD 1.59 in discounted benefits.

A simple sensitivity analysis shows that the NPV remains positive as long as the electricity tariff does not fall below USD 0.07 per kilowatt-hour or the operating cost does not exceed ten percent of the investment ranges that are still reasonable under practical conditions. Even if the availability factor decreases from 0.80 to 0.70 due to operational interruptions at the power plant, the NPV remains around USD 5,000 and the IRR stays above fifteen percent. The main risks lie in potential reductions in the internal electricity tariff or unexpected microturbine failures; however, both can be mitigated through manufacturer service contracts, the costs of which are already included in the estimated annual O&M budget.

Overall, all classical financial indicators positive NPV, IRR well above the WACC, BCR greater than one, and a short payback period collectively affirm the project’s economic feasibility. Compared to other energy-efficiency investments in the coal-fired power sector, this project requires modest capital, adds no fuel consumption, and provides stable cash flows with manageable risk. Therefore, the utilization of flue-gas emissions from the Adipala Power Plant to generate five kilowatts of electricity can be recommended not only as a technical demonstration project but also as a profitable asset-management strategy for thermal power facilities.

CONCLUSION

The study confirms that Adipala’s economizer flue gas ($55,000 \text{ kg h}^{-1}$ at $170 \text{ }^{\circ}\text{C}$) contains sufficient enthalpy ($\sim 400 \text{ kW}_{\text{th}}$) to support a 5 kW micro-ORC producing net output while

keeping exhaust at 110 °C and backpressure below 2 mbar, thereby avoiding interference with boiler operation. Financial analysis under conservative assumptions (CAPEX USD 15,000; tariff USD 0.10 kWh⁻¹; discount rate 10%) yields positive NPV (~USD 11,000), IRR ≈ 19.8%, BCR 1.59, and payback ≈ 4.9 years, demonstrating economic feasibility for a twenty-year horizon. Overall, the project meets the research objectives by establishing both technical viability and attractive economic returns for small-scale waste-heat recovery at Adipala. Evaluate long-term operational impacts on boiler fouling and corrosion under varying load cycles using multi-year DCS/CEMS records; perform a pilot installation to measure real auxiliary loads and dynamic availability; conduct a life-cycle assessment including embodied emissions of the ORC skid and potential carbon revenue scenarios to quantify net environmental benefits; and assess regulatory and grid-integration arrangements for internal supply or sale to PLN to refine revenue assumptions.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to PT Indonesia Power, Unit Jasa Pembangkit (UJP) Jawa Tengah 2 Adipala, for providing access to operational data and technical information essential to this study. Appreciation is also extended to the Ministry of Energy and Mineral Resources of the Republic of Indonesia (ESDM) for policy documentation that supported the contextual analysis. The authors acknowledge the valuable guidance and discussions contributed by colleagues from the Department of Mechanical Engineering and Energy Systems, whose insights greatly enriched the thermodynamic and economic evaluations. This research was conducted independently for academic purposes; all interpretations, analyses, and conclusions are the responsibility of the authors and do not necessarily represent the official position of PT Indonesia Power or any other affiliated institution.

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