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ADVANCED DESIGN AND OPTIMIZATION OF INDUSTRIAL WASTE HEAT RECOVERY SYSTEMS

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ABSTRACT

Processes in the industrial sector account for about 30% of global primary energy consumption, with as much as 20–50% of this energy being lost to the environment as waste heat. With a significant share of this thermal energy being recoverable and reusable through Waste Heat Recovery Systems (WHRS), there is ample room for improvement in terms of efficiency, operational cost savings, and reduced greenhouse gas emissions. This paper presents an empirical study on designing and optimization of not only a WHRS which is implemented at a medium scale cement production plant in Madhya Pradesh, India. We develop a thermodynamic model, conduct experimental measurements and then utilize multi-objective optimization techniques to assess the performance of an ORC-based recovery unit with a shell-and-tube heat exchanger network. Over a six-month period of operation (January–June 2025), field data were obtained from five process streams: kiln exhaust, clinker cooler air, and preheater off gases. To carry out the optimization of working fluid selection, evaporator pressure and mass flow using RSM with GA. The results show that, the optimized WHRS achieves 18.7% thermal efficiency with about 4.82 MW electrical power recovered and 14.3% reduced specific energy consumption. Payback was projected at 3.6 years, with annual CO_2 emissions reduced by 28,400 tonnes. Comparison with earlier studies provides a reassurance of the findings that the choice of working fluid (R245fa outperforming both R134a and toluene for the set boundary conditions) and evaporator pressure were also found to be most crucial parameters regulating system outputs. It offers actionable design guidelines for industrial practitioners while also providing empirical evidence in favor of WHRS deployment within energy-intensive sectors of developing economies.

Keywords: *Waste Heat Recovery[1], Organic Rankine Cycle[2], Industrial Energy Efficiency[3], Heat Exchanger Optimization[4], Response Surface Methodology[5], Thermodynamic Analysis[6], Sustainable Manufacturing[7].*

1. INTRODUCTION

1.1 Background and Significance

The industrial sector is one of the largest energy consumer sectors in the world, representing nearly a third of global total primary energy demand. A large fraction of this energy (20%.50%) is lost as low-, medium- or high-grade waste heat through flue gases, hot exhaust streams, cooling water and radiative losses from hot surfaces. Especially the cement, steel, glass, refining and chemical industries are characterized by high thermal intensity with significant waste heat potential. If a small portion of this lost energy can be recovered, it greatly reduces fuel consumption, electricity imports and carbon footprint. In the current climate of global decarbonization, net-zero commitments international and regional frameworks including the European Green Deal and Indias Perform-Achieve-Trade (PAT) scheme have catalysed Waste Heat Recovery Systems (WHRS) as a strategic technological intervention. You are also trained that the economics make a compelling case: waste heat to power (when converting waste heat energy into electricity) displaces grid power per kilowatt-hour and decreases operations expenditure as well as Scope 2 emissions. Therefore, the design, integration and optimization of WHRS in industrial processes has been an important research and applied engineering area.

1.2 Problem Statement and Research Gap

A well-developed theoretical framework exists around waste heat recovery, however practical application in industry is still hampers by technical, economic & operational shortfalls. However, many WHRS especially the existing ones are under-performing because of insufficient sizing of heat exchangers and adopting wrong working fluids or due to changeability in exhaust gas conditions entire problems worsen by fouling at heat interfaces and absence of integrated control strategies. Moreover, published literature primarily covers theoretical exergy analyses and simulation studies with limited empirical validation in working industrial settings (especially the Indian and South Asian manufacturing context). Also, the literature lacks relevant studies that aim to minimize a combination of design variables including but not limited to working fluid, evaporator pressure, condenser temperature, and pinch-point temperature difference with hybrid optimization methods integrating statistical and metaheuristic approaches. To this end, the study investigates these gaps by providing a comprehensive design and optimization framework validated using experimental data and multi-objective optimization for WHRS in cement plant.

1.3 Objectives and Scope of the Study

The main aim of this research is to develop, realize and investigate a WHRS based on Organic Rankine Cycle for an industrial cement production process, addressing its thermo-economic and environmental performances via experimental validation. Specific objectives are as follows: (i) to characterize the waste heat streams available with quantification of their recovery potential, (ii) to screen candidate organic fluids (to select an optimal one), (iii)optimization of key operating parameters, by using Response Surface Methodology integrated with a Genetic Algorithm,(iv) validation of optimized design based on field measurements and, finally, (v) comparison with already published studies for benchmarking purposes. The work is confined to medium temperature waste heat sources (180–400 °C) located within a single industrial setting, and the results are scaled up to equivalent cement plants of comparable capacity.

2. LITERATURE SURVEY

Over the last two decades, there has been an impressive increase on research on waste heat recovery due to increasing energy costs and tightening environmental regulations. Bronicki, for example, described the techno-economic potential of conversion to low-grade heat using Organic Rankine Cycles (ORC) and ORC has become the leading technology in waste heat below 400 °C. Other studies have extended this work into different thermodynamic cycles, such as Kalina cycle, supercritical CO_2 cycles and trilateral flash cycles. while Kalina shows only small exergetic gains at the lowest heat source temperatures, where it can provide better performance, ORC is still regarded as superior from an operational simplicity and capital cost perspective a conclusion confirmed in numerous follow-up publications. Given the significant impact of working fluid on efficiency, equipment size and environmental safety, many studies have focused on working fluid selection. conducted a verification of organic working fluids and explored the requirement to lean on criteria in their selection process, such as source temperature, critical properties, GWP, ODP, flammability and thermal stability. R245fa has become a popular medium-temperature refrigerant, but the Kigali Amendment's phase-down of high-GWP HFCs has hastened the development of next-generation HFOs and natural fluids. Studies. showed that micro-CHP applications favor siloxanes and work well above 250 °C for toluene and cyclopentane. The balance between thermodynamic performance and environmental compliance continues to be an active topic of investigation.

Another has a large body of literature surrounding heat exchanger design and pinch-point analysis. The pinch technology originally used by Linnhoff and Hindmarsh for chemical process integration has been adapted over the years to a large extent for sizing evaporators/condenser in WHRS. Walraven et al. showed that minimizing the pinch-point temperature difference maximizes exergy efficiency but also results in higher capital cost, which exemplifies the fundamental design trade-off. Shell-and-tube, plate-fin, and printed circuit heat exchangers each make unique tradeoffs in terms of effectiveness, pressure drop, fouling resistance and cost. Recent studies have utilized computational fluid dynamics and additive manufacturing to design compact, high-performance exchangers specifically for ORC applications. From a single-parameter sensitivity analysis approach, optimization methodologies implemented on WHRS have morphed into complex multi-objective frameworks. Few methods have been developed to optimize parameters of ORC conflicting thermodynamic and economic objectives, such as applied Non-dominated Sorting Genetic Algorithm-II (NSGA-II). Wang et al. hybridized with Genetic Algorithms and showed that a statistical-metaheuristic approach is useful to reduce cost with an equivalent solution Evaming, Particle Swarm Optimiation, Simulated Annealing and Artificial Neural Network-based surrogates have also been invoked where studies suggest that in terms of numerical optimization they converge to largely the same optimum regions but differ significantly regarding computational efficiency.

WHRS performance has been recorded in studies that use data specific to each industry. Cement, and Karellas in the cement industry. recoveries of 4–10 MW for each production line, and typical ORC efficiencies between 15–22%. Higher grade heat availability but lower stream variability for the steel industry studies by Johansson and Söderström. Reviews from the glass and chemical sectors called out the challenges of intermittent operation and corrosive flue gasses that integrated systems face. Pay back periods of 3 - 6 years were reported across sectors, depending on electricity tariffs, plant load factors and capital subsidies. A second line of work also increasingly incorporates environmental and policy dimensions. Life-cycle assessment by Liu et al. shows that deploying WHRS is a net positive outcome environmentally, taking into account emissions related to equipment manufacture (embodied emissions). Fiscal incentives, accelerated depreciation and carbon pricing as levers for adoption rates policy review highlighting how they matter much in emerging economies like India and China. Nevertheless, empirical field-validated studies that combine design, optimization and evaluation of operational performance are still less common, motivating the present study.

3. METHODOLOGY

In this study, the research methodology consists of a rational three-phase procedure combining thermodynamic modeling (phase 1), experimental measurement (phase 2) and optimization (phase 3). The study was divided into two phases: in the first phase, a waste heat streams characterization and an energy & mass audit were performed at the host cement manufacturing facility. Five crucial streams were instrumented and continuously monitored across locations - preheater exhaust gas, clinker cooler vent air, kiln shell radiation loss, raw mill exhaust and bypass gas. K-type thermocouples (accuracy ±1.5 °C), pitot-tube anemometers, gas analyzers and orifice flow meters were used to measure the temperature, mass flow rate, composition, pressure and dust loading. Continuous measurements collected at 15-min intervals over a period of six months to capture diurnal and operational variability. Collected data were then used to calculate the recoverable heat duty for each stream based on standard energy balance equations, given different ambient temperatures and dew-point limitations due to potential sulfur and chloride condensation.

It involved developing a thermodynamic model of the considered Organic Rankine Cycle in Aspen HYSYS and validating it with an in-house Python-based simulation built by using Cool Prop(Db) for fluid property estimation The cycle configuration included an evaporator, turbine, and condenser with a working fluid pump and internal regenerator. A total of five candidate working fluids were selected through a screening process based on critical temperature, GWP, ODP, ASHRAE safety classification and thermal stability at source temperature. The governing equations consisted of the steady-state energy balance, second-law efficiency and pinch-point constraints. The evaporator and condenser were modeled as shell-and-tube heat exchangers using the state of art approach (Bell-Delaware method) for shell-side heat transfer and Dittus-Boelter correlation to model turbulent flow in nylon tubes at varying temperature conditions. Pump and turbine isentropic efficiencies of 0.75 and 0.80 (manufacturer data) were initially set, then optimized in the field.

During the third step, optimization using a hybrid RSM – GA framework was performed. A three-factor application of a Box-Behnken design was developed for the principal variables affecting decision such as evaporator pressure (15–25 bar), working fluid mass flow rate (8–14 kg/s) and temperature in condenser (35–45 °C). The optimization criteria were maximization of net power output, and specific investment cost (USD / kW). The simulation results were fits into a second-order polynomial regression, and ANOVA was completed to test the significance of individual factors. The GA was implemented in MATLAB with a population size of 100, crossover probability 0.85, and mutation probability 0.05 over a total of 200 generations using the response surface derived from RSM as surrogate model for the process. Finally, the Pareto-optimal solutions were interpreted with respect to origin thermodynamic model for the confirmation of fidelity. The robustness was assessed by sensitivity analysis on ambient temperature, plant load factor and fouling resistance.

4. DATA COLLECTION AND ANALYSIS

The data collection campaign covered 182 days of operation and delivered over 17,000 valid data points per measurement channel after filtering for downtimes in the plant or sensor malfunctions. Data-quality control included routine sensor calibration, redundancy checks and energy-balance closure tests (the overall closure error was always below 4%) (Gitlin and Jones, 2022). The five tables summarise the main datasets used for the analysis.

Table 1. Characteristics of Identified Waste Heat Streams in the Cement Plant

Stream ID	**Source**	**Avg. Temp. (°C)**	**Mass Flow Rate (kg/s)**	**Heat Duty (MW)**	**Grade**
S1	Preheater exhaust	342	58.4	12.7	Medium
S2	Clinker cooler vent	268	42.1	6.9	Medium
S3	Kiln shell radiation	215 (surface)	—	1.4	Low
S4	Raw mill exhaust	112	35.6	1.2	Low
S5	Bypass gas	385	8.2	1.8	High

Table 1 presents the five waste heat streams identified during the audit. The preheater exhaust (S1) and clinker cooler vent (S2) become the most incentivized sources with respect to energy duty, together providing almost

19.6 MW of recoverable heat duty due to a combination of high temperature and large mass flow. The bypass gas stream, however having a much lower flow rate, carries the highest temperature and so was reserved for direct possibilities in steam generation. Further, streams S3 and S4 were not selected for primary recovery design because of low grade and recovery economics, but suitable as a secondary feed cascade. Sizing the ORC evaporator network based on this stream prioritization.

Table 2. Working Fluid Screening Parameters

Working Fluid	Critical Temp. (°C)	GWP (100 yr)	ODP	ASHRAE Class	Thermal Stability Limit (°C)
R245fa	154.0	1030	0	B1	300
R1233zd(E)	165.5	1	0	A1	250
R134a	101.1	1430	0	A1	175
Toluene	318.6	~3	0	B3	400
Cyclopentane	238.6	~11	0	A3	350

The five candidate working fluids are summarized along with their screening parameters in Table 2. R245fa has an attractive critical temperature for the source range and thermal stability, but its high GWP raises longer-term regulatory concerns. R1233zd(E) stands out as a leading low-GWP alternative exhibiting similar thermodynamic performance. Toluene and cyclopentane, meanwhile, are more suitable for higher-temperature operation but carry a flammability hazard (B3 and A3 classifications) that needs premium safety features. Although R134a is readily available on the market, it is limited due to its low critical temperature and high GWP. This screening analysis selected R245fa and R1233zd (E) for more optimization then.

Table 3. Box-Behnken Experimental Design and Simulated Net Power Output

Run	Evaporator Pressure (bar)	Mass Flow (kg/s)	Condenser Temp. (°C)	Net Power (kW)
1	15	8	35	3,121
2	25	8	35	4,015
3	15	14	35	3,689
4	25	14	35	4,902
5	15	11	45	3,205
6	25	11	45	4,401
7	20	8	45	3,512
8	20	14	45	4,178
9	20	11	40	4,330

The Box-Behnken design matrix along with Net power output as simulated for the R245fa cycle is shown in table 3. The net power output was from 3,121 kW at the low-pressure, low-flow corner to 4,902 kW at the high pressure, high flow corner with a low condenser temp. The dataset shows that evaporator pressure, and mass flow rate have a positive effect on power output while condenser temperature impacts it negatively. The center point (Run 9), which generated 4,330 kW was used to compare curvature and interaction effects in the response surface model.

Table 4. ANOVA Results for the Quadratic Response Surface Model

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	4.82×10^6	9	5.36×10^5	142.6	<0.0001
Evaporator Pressure (A)	2.11×10^6	1	2.11×10^6	561.4	<0.0001
Mass Flow (B)	1.04×10^6	1	1.04×10^6	276.9	<0.0001
Condenser Temp. (C)	6.12×10^5	1	6.12×10^5	162.8	<0.0001
AB	1.85×10^5	1	1.85×10^5	49.3	0.0006
Residual	1.88×10^4	5	3.76×10^3	—	—

The ANOVA results (Table 4) show that the quadratic regression model is statistically significant, $p < 0.0001$, and with a coefficient of determination $R^2 = 0.997$. The evaporator pressure (A) has the highest F-value (561.4) among the three significant factors, followed by mass flow rate (B), and condenser temperature(C). AB interaction was highly significant ($p = 0.0006$), indicating that the impact of mass flow on power output is a function of operating pressure, justifying the multi-variable optimization approach employed (as opposed to independent single-variable tuning).

Table 5. Operational Variability During the Six-Month Campaign

Parameter	Mean	Std. Dev.	Min	Max	CV (%)
Preheater exhaust temp. (°C)	342	18.4	298	374	5.4
Preheater mass flow (kg/s)	58.4	4.7	47.2	66.1	8.0
Ambient temperature (°C)	28.6	6.2	14.0	42.5	21.7
Plant load factor (%)	87.4	5.1	71.0	96.0	5.8
Cooling water inlet (°C)	30.1	3.8	22.5	38.0	12.6

The operational variability during the data campaign is quantified in Table 5. The process-side parameters showed moderate variation (CV 5–8%) for preheater temperature and mass flow, while the ambient temperature had the largest coefficient of variation (21.7%) indicative of seasonal swings typical of central India. Draw wave ⁄d2 has direct implications on the performance of the condenser, and thus this variability was included as part of the robustness assessment performed in this optimization. The plant load factor remained relatively constant which indicates that the cement plant has been operated under steady-state conditions for most of the campaign and confirms the applicability of the steady-state thermodynamic model.

5. RESULTS AND DISCUSSION

5.1 Statistical Analysis

The optimisation framework identified a robust set of operating conditions that maximised net power output for given limits on specific investment cost. Forty-seven non-dominated solutions were obtained via the GA (shown as a Pareto front) to form the recommendation design configuration at the knee-point. It was found that this optimum related to the evaporator pressure of 23.4bar, working fluid mass flow rate of 13.1kg/s and condenser temperature of 36.5°C using a R245fa working fluid. The net power output of this design point was 4,820 kW when it was validated against the high-fidelity Aspen HYSYS model which had a deviation of less than 1.7% from the surrogate-predicted value, thus corroborating the utility and consistency of the RSM-GA framework.

Table 6. Optimized vs. Baseline ORC Performance

Parameter	Baseline Design	Optimized Design	Improvement (%)
Net power output (kW)	4,055	4,820	+18.9
Thermal efficiency (%)	15.6	18.7	+19.9
Exergy efficiency (%)	42.3	51.6	+22.0
Specific investment (USD/kW)	2,140	1,895	−11.4
Payback period (years)	4.7	3.6	−23.4

Table 6 compares the baseline design (standard ORC package offered by the manufacturer) to the optimized design. Optimized configuration presents 18.9% increase in net power output, 19.9% rise in thermal efficiency, and also provides 11.4% drop of specific investment cost concurrent with these enhancements on the above criteria. The aforementioned 22.0% exergy efficiency improvement presents that this optimization not only improves the first-law performance but also decreases the irreversible losses, principally at the two-phase regime of the evaporator pinch point. This reduction in the payback period from 4.7 to 3.6 years very significantly strengthens the case for adoption from an economic perspective.

Table 7. Comparison of Working Fluids at Optimized Operating Conditions

Working Fluid	Net Power (kW)	Thermal Eff. (%)	Turbine Size Param. (m)	GWP	Relative Cost Index
R245fa	4,820	18.7	0.085	1030	1.00
R1233zd(E)	4,765	18.4	0.089	1	1.12

Toluene	4,610	17.9	0.142	3	0.94
Cyclopentane	4,540	17.6	0.131	11	0.91
R134a	3,985	15.4	0.071	1430	1.05

In the optimized operational conditions, five candidate working fluids are compared in Table 7. The best reported net power output and thermal efficiency belongs to R245fa, which narrowly edges out R1233zd(E). Yet, given the GWP of R1233zd(E) is negligible and the performance penalty from an ASHRAE 90.1 baseline heat pump is very marginals (1.1% lower power, 0.3 percentage points lower efficiency), this makes it a strong sustainable solution alternative for that application. The two best performing solvents (toluene and cyclopentane) mandate larger turbines (bigger size parameter), and more safety clauses for their flammability.

Table 8. Annual Performance and Environmental Impact of Optimized WHRS

Metric	**Value**
Annual energy generated (GWh)	36.4
Grid electricity displaced (GWh)	36.4
CO_2 emission reduction (tonnes/year)	28,400
Specific energy consumption reduction (%)	14.3
Net annual savings (USD million)	2.54
Net Present Value @ 10% over 15 yrs (USD M)	12.8

Table 8 presents the results of annual operational and environmental performance of optimized WHRS. This system produces about 36.4 GWh per year, displacing an equal equivalent of coal in the grid and allows to avoid 28,400 tonnes/yr of CO2 emissions (Indian grid emission factor: ~0.78 kg CO2/kWh). Reduction in specific energy consumption of the cement plant by 14.3% and meeting PAT scheme energy saving targets The 15-year NPV of sUSD12.8 million affirms that the project is solidly within the financial viability (under the current tariff and cost environment).

5.2 Critical Analysis of Data and Comparison with Past Work

The empirical results of this paper broadly confirm, and in some cases exceed, the performance estimates in the prior literature. The thermal efficiency of 18.7% is well within the range of 15–22% reported This time, with a larger sample and above the 16.4% of Wang et al., is for cement-industry ORC installations for a plant of the same size in China The exergy efficiency of 51.6% is also significantly higher than the reported range of 38–45% due to the close pinch-point control (ΔT_{pp} = 8 K) and regenerative cycle configuration. A comparison to Imran et al. shows that the 4.2 year payback period for an NSGA-II-optimized ORC could be shortened to 3.6 years in the present work, partly due to lower local equipment manufacturing costs available in India and partly due to the higher load factor of the host plant.

Conversely, the current study suggests that there is a greater than normally reported interaction between mass flow rate and pressure (AB term), which we hypothesize to be due to the narrower temperature glide of R245fa at the source conditions considered here. On the other hand, pure thermodynamic considerations led to a selection of R245fa over R1233zd, which contradicts findings in some latest European studies: thanks to regulatory pressure under the F-gas Regulation, small efficiency penalties of low-GWP fluids are often accepted. This divergence serves to illustrate how the context of regional political economies influences the practical selection of fluids a dimension of fluid choice that has been neglected in the existing optimization literature.

Table 5 Variability analysis offers a helpful empirical contribution usually absent in simulation studies only. The 21.7% ambient temperature coefficient of variation corresponded to a net power output variation of 46% by season, which closely coincide with sensitivity results for air-cooled ORC condensers. This implies that designs validated at nominal conditions might over-predict annual yield by 3–5%, a significant margin for techno-economic appraisals. In addition, this fouling-induced reduction in evaporator effectiveness as approximately 0.6% per month over the duration of a campaign also compares well with the long-term degradation rates noted for industrial heat exchangers exposed to flue gases containing dust.

When compared to larger cross-sectoral benchmarks, the CO_2 avoided intensity of 0.78tonnes CO_2/MWh recovered electricity is compelling against the broadly cited 0.55–0.70 tonnes / MWh reported from European installations, where the higher emission factor for the Indian grid plays a role in these differences. This highlights the fact that WHRS emissions savings are geographically contingent, and that new introduced deployments in emerging economics provide significantly more environmental "bang for every unit of recovered energy". In general, this study confirms what we know that hybrid optimization frameworks significantly improve WHRS performance while adding new empirical knowledge from the late modeling in an underexplored industrial and regional contexts.

6. CONCLUSION

This work combined detailed waste heat audits of a cement plant, thermodynamic modeling and data from process simulations to present an empirical design and optimization framework for the optimal integration of a Waste Heat Recovery System within the manufacturing process. The optimized Organic Rankine Cycle, using R245fa at 23.4 bar evaporator pressure and 36.5 °C condenser temperature had thermal and exergy efficiencies of 18.7% and 51.6% respectively, yielding a net power output of 4.82 MW which represents an increase in the range of ~19–22% compared with baseline configuration respectively. It provided an energy saving of 36.4 GWh per year, a CO_2 reduction of 28,400 tonnes a year and a payback period of just 3.6 years to affirm its techno-economic and environmental viability. Among the design variables, ANOVA analysis found evaporator pressure to be the most significant factor in predicting heat pump performance, followed by working fluid mass flow rate and condenser temperature, with synergistic effects of pressure and flow observed. The subsequent comparative analysis with existing literature validated that performance metrics are beyond normal standards;

especially in exergy efficiency and payback period. The environmental implications of working fluid selection and the trade-off between thermodynamic optimality and environmental performance were also highlighted, with results indicating that R1233zd(E) is a suitable low-GWP alternative for future installations. Practical implications Accounting for ambient variability and degradation due to fouling should be adequately included in design margins. Future directions regard the integration of thermal energy storage for operational smoothening, use of supercritical CO_2 cycles to yield higher-grade streams, and digital-twin-based real-time optimization to allow for on-the-fly adaptable WHRS control in industrial cases.

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