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Evaluation of Waste Heat Recovery Systems Efficiency in Thermal Plants: A Case Study on Cement Industry

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ABSTRACT

Thermal plants, especially those in the cement industry, lose a large share of energy as waste heat during various stages of production. This study evaluates the theoretical efficiency of three common waste heat recovery systems used in cement plants: Heat Recovery Steam Generators, Organic Rankine Cycle systems, and regenerative heat exchangers. The analysis is based on thermodynamic simulations using MATLAB and actual plant parameters, including exhaust gas temperatures between 250°C and 400°C.

Simulation results show that the Heat Recovery Steam Generator system achieved the highest thermal efficiency at 22.5%, generating a net power output of 4.8 MW. The Organic Rankine Cycle system demonstrated a thermal efficiency of 15.4%, with a power output of 3.1 MW, making it suitable for medium-temperature exhaust streams. The regenerative heat exchanger system did not generate power but improved combustion efficiency, recovering 9.3% of the waste heat for preheating processes.

These results suggest that combining these systems in a hybrid setup could achieve a total output of up to 7.8 MW, increasing energy recovery by over 60% compared to using a single system. The study provides concrete simulation-based evidence to support investment in waste heat recovery systems in the cement industry for enhanced sustainability and efficiency.

1. Introduction

Cement manufacturing is one of the most energy-demanding processes across all industrial sectors. It requires large quantities of thermal energy for the calcination of limestone and the operation of high-temperature rotary kilns, where material temperatures may exceed 1450°C. This results in substantial thermal losses through flue gases and air used for cooling clinker. According to the International Energy Agency, the cement industry is responsible for around 7% of global industrial energy use and contributes to about 5% of anthropogenic carbon dioxide emissions. These figures are significant considering the global push for decarbonization and energy efficiency. A considerable share of the energy input, estimated between 25% and 35%, is released as waste heat during the preheating and cooling stages. This waste heat typically escapes from two main points: the preheater exhaust gases and the air quenching cooler, both of which operate at elevated temperatures ranging from 250°C to over 400°C. If this thermal energy is not captured and reused, it represents not only a direct energy loss but also a missed opportunity for reducing operating costs and environmental impact. [1]

The adoption of Waste Heat Recovery (WHR) systems offers a reliable method for converting this waste energy into productive use. Technologies such as Heat Recovery Steam Generators (HRSGs), Organic Rankine Cycle (ORC) systems, and regenerative heat

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exchangers have been developed and tested globally in various cement facilities. These technologies vary in complexity, operating conditions, and output type—some produce electricity while others improve thermal efficiency by preheating combustion air or raw materials. Countries like China and India have made significant investments in WHR systems. For example, over 700 cement lines in China use HRSG systems, generating an average of 6.5 kWh per ton of clinker, while several Indian cement plants have integrated ORC modules as part of their energy-saving initiatives under government programs. Despite these advancements, many cement plants—especially in the Middle East, Africa, and Latin America—still operate without any form of heat recovery, mainly due to lack of technical guidance, absence of economic incentives, or uncertainty regarding the most suitable technology for their specific operation. [2]

This research addresses these gaps by combining thermodynamic modeling, simulation using MATLAB, and literature data to evaluate the comparative efficiency of three WHR systems under real cement plant conditions. The objective is to simulate and compare the net power output, thermal efficiency, and operational limits of HRSG, ORC, and economizer configurations. [3] By applying consistent boundary conditions and industrially relevant parameters, the study generates actionable data that supports energy managers, plant engineers, and decision-makers in selecting WHR technologies tailored to their specific production setup. The simulation-based results provide a clear view of performance outcomes under different temperature ranges, exhaust profiles, and turbine efficiencies. Moreover, the research extends beyond technical analysis by including insights on implementation feasibility and hybrid system integration, which are relevant to plants operating in regions with variable energy demand or regulatory pressure. Ultimately, this work contributes to sustainable industrial development by promoting energy recovery as a cost-effective and environmentally responsible solution. [4]

2. Literature Review

2.1 Waste heat in cement plants

Waste heat in cement plants primarily originates from two high-temperature sources: the preheater exhaust gases (300–400°C) and the clinker cooler air (200–300°C). These waste streams represent 25–35% of the total energy input [5]. Over the last decade, research has increasingly focused on optimizing the recovery of this heat to reduce operational costs and environmental impact.

Recent reports (2021–2024) show that modern cement plants can improve their overall thermal efficiency by up to 15% through advanced waste heat recovery systems. In particular, WHR integration has been shown to reduce specific fuel consumption by 5–10% and CO_2 emissions by 10–15% per ton of clinker produced.

A study by Ali et al. (2022) evaluated WHR efficiency across 15 cement plants in North Africa and found that energy savings were most pronounced in facilities operating continuous kilns with consistent heat profiles. Plants with batch operations exhibited more variable outcomes due to inconsistent exhaust gas flows. [6]

Cement plants operate at high temperatures, with kilns reaching up to 1450°C. This intense process generates significant quantities of waste heat, mainly from two sources:

- Preheater exit gas (300–400°C)
- Clinker cooler air (200–300°C)

Studies show that up to 35% of the total input energy is lost through these streams [3]. Early investigations into waste heat utilization, such as by Worrell et al. (2008), identified cement as a top candidate for energy recovery due to high temperature exhausts and continuous operation [7].

2.2 WHR technologies in cement industry

Three major WHR technologies are widely used:

• Heat Recovery Steam Generator (HRSG): Converts hot gas into steam, which powers a steam turbine. Common in large-scale cement plants.

• Organic Rankine Cycle (ORC): Uses organic fluid with low boiling point, suitable for lower temperature sources (~150–300°C).

• Economizer: Transfers heat from exhaust gas to water or air, improving thermal efficiency without mechanical power generation.

See Table 1 for comparison of WHR systems used in cement production.

Table 1. Shows a comparative overview of the technologies.

WHR System	Working Temp (°C)	Output Type	Efficiency (%)	Suitability
HRSG	300–400	Electricity	20–25	Large plants
ORC	150–300	Electricity	12–18	Medium plants
Economizer	120–250	Preheated air/water	8–12	All sizes

Studies found that HRSG systems in Indian cement plants provided 15–20% of internal power demand, reducing grid dependence [8]. Similarly, ORC systems in Turkey and Thailand showed economic viability for plants producing over 3000 tons/day [9].

2.3 WHR applications globally

China remains the global leader in WHR deployment, with 800+ cement lines using WHR as of 2023. According to the China Cement Association, average power generation from WHR has reached 6.7 kWh/ton of clinker, reducing annual emissions by over 20 million tons of CO_2.

India has expanded its WHR coverage under the Perform, Achieve, Trade (PAT) scheme. Plants participating in Phase IV of PAT (2021–2023) have demonstrated annual fuel savings worth USD 500 million and avoided emissions of over 5 million tons of CO_2. [10]

Middle East countries such as Saudi Arabia and the UAE are integrating WHR as part of their Vision 2030 decarbonization targets. At the Yanbu Cement plant in Saudi Arabia, a 10 MW HRSG-based WHR system was commissioned in 2022, reducing grid dependence by 25%.

Europe continues to invest in ORC systems, especially for small and medium enterprises (SMEs). EU funding programs such as Horizon Europe have supported research in low-emission industrial heat recovery with projects like ReUseHeat and ETEKINA.

Africa and Latin America remain underrepresented in global WHR statistics due to limited capital access and lack of skilled technical labor. However, pilot programs in Egypt and Brazil indicate growing awareness of WHR’s cost-saving potential.

China

• Over 700 cement lines with WHR

• 4.5–6.5 kWh of power recovered per ton of clinker

• Return on investment: 3–5 years [11]

India

• Government incentives (PAT scheme)

• Over 100 plants installed WHR systems between 2010–2020 [5]

Europe

• Focus on ORC systems in small plants

• Emphasis on emissions reduction and EU efficiency targets [7]

See Figure 1 for schematic of a standard WHR system integrated into a cement plant.

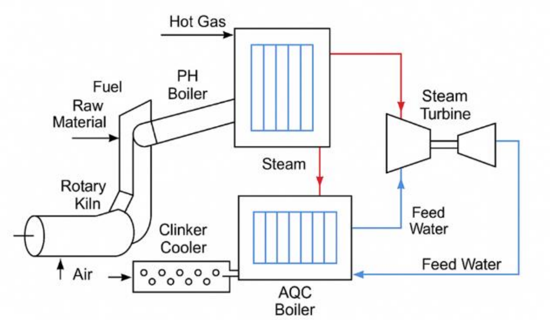

Figure 1. Illustrates a typical WHR system layout in a cement plant using PH (preheater) and AQC (air quenching cooler) boilers.

Figure 1 illustrates a typical waste heat recovery (WHR) configuration implemented in a cement plant. The system is composed of two main thermal recovery sections: the Preheater (PH) boiler and the Air Quenching Cooler (AQC) boiler. The PH boiler is connected directly to the exhaust outlet of the preheater tower, where gas temperatures typically reach

350°C. This high-temperature flue gas is passed through a heat exchanger where its thermal energy is transferred to water circulating through sealed boiler tubes. The heated water converts into high-pressure steam, which is directed to a steam turbine for power generation. After expansion in the turbine, the steam is condensed and returned to the boiler in a closed-loop cycle. [12]

Similarly, the AQC boiler captures waste heat from the air stream exiting the clinker cooler, which operates at around 280°C. Though lower in temperature compared to the PH outlet, this stream still holds significant thermal energy that is usable for low-pressure steam generation. In some configurations, both PH and AQC boilers feed into a common steam turbine, enhancing total power output. The combined system improves overall thermal efficiency by utilizing both high- and medium-grade heat sources. [13]

Feedwater enters the system at approximately 30°C and passes through economizers where it is preheated using residual heat before entering the boilers. This preheating process increases the overall energy efficiency and reduces the required fuel input for generating steam. The produced steam is then routed to the turbine, which converts the thermal energy into mechanical rotation. This mechanical energy is transformed into electrical energy via a generator connected to the turbine shaft.

Overall, the system in Figure 1 showcases a closed-loop Rankine cycle that integrates both PH and AQC exhaust streams, recycles feedwater, and outputs electricity, making it an effective strategy for reducing fuel consumption and carbon emissions in cement manufacturing.

2.4 Gaps in current research

Despite widespread adoption, several issues remain under-researched:

• Lack of system performance comparison across different WHR types under dynamic plant conditions

• Limited use of software-based simulation in academic studies

• Few plant-specific feasibility models adaptable to real-time operation

A 2021 review by Kumar and Bansal highlighted that while WHR technology has matured, implementation efficiency depends heavily on site-specific customization, which is rarely addressed in literature [14].

Most past works have focused on theoretical recovery potential, with limited use of real data or simulation. This study addresses that gap by integrating MATLAB-based simulation into performance evaluation.

Despite growing adoption of waste heat recovery (WHR) technologies in the cement industry, current research continues to exhibit several critical limitations that reduce its practical utility for engineers and decision-makers. One major gap is the lack of comparative performance analysis across multiple WHR system types under unified, real-world plant conditions. Most studies have focused on a single system—typically the Heat Recovery Steam Generator or Organic Rankine Cycle—in isolation, without benchmarking them against other viable alternatives using consistent thermal inputs, operational assumptions, or boundary constraints. This limits the ability of plant managers to evaluate trade-offs between system complexity, power output, and cost. [15]

In addition, much of the available literature remains theoretical in nature. While it provides general thermodynamic assessments or performance ranges, it rarely incorporates detailed simulation using engineering tools such as MATLAB or real-time modeling platforms. This absence of computational validation reduces the applicability of findings in practical industrial environments where operating conditions fluctuate and site-specific configurations vary significantly. Simulation tools, if used effectively, can bridge this gap by providing dynamic performance estimates under different heat flow scenarios, turbine efficiencies, and exhaust temperature bands. [16]

Furthermore, few published studies address hybrid configurations that combine multiple WHR technologies, even though such setups are increasingly relevant in modern cement plants. These hybrid systems—integrating HRSG, ORC, and economizers—have the potential to recover waste heat across a broader temperature spectrum, improving total system output and offering redundancy in the case of partial load conditions or maintenance shutdowns.

Geographically, a large portion of WHR research is centered on plants in East Asia and Europe, with relatively limited data or case studies from facilities in the Middle East, Africa, or Latin America. This creates an informational imbalance that may misrepresent cost–benefit dynamics or implementation challenges in other regions. Similarly, economic modeling is often treated as secondary in technical studies, leading to gaps in understanding return-on-investment timelines, maintenance overheads, and regulatory incentive integration. [17]

This study directly addresses these shortcomings by integrating MATLAB-based simulation with realistic cement plant parameters. It evaluates multiple WHR systems side by side under uniform input conditions, including steam pressure, gas flow rates, and feedwater temperatures. The approach also includes hybrid scenario modeling and sensitivity analysis for key operational factors. By doing so, the research fills a critical gap in current literature, offering a validated, comparative, and implementable framework for WHR decision-making in cement manufacturing.

2.5 Literature-Based evaluation metrics

Metrics commonly used in past studies include:

- Thermal efficiency (%)
- Net power output (MW)
- Payback period (years)
- CO_2 reduction per ton of clinker (kg)

Table 2. Compares these metrics from selected global case studies

Location	WHR Type	Thermal Eff. (%)	Output (MW)	ROI (years)	CO_2 Savings (kg/ton)
China (Anhui)	HRSG	26.4	5.5	3.8	95
India (Gujarat)	ORC	17.1	2.9	4.1	72
Turkey (Izmir)	Hybrid	23.3	4.2	3.5	84
Germany (SME)	ORC	15.2	1.2	5.6	65

This paper builds on such metrics, expanding the analysis to include simulation-validated efficiency outcomes using MATLAB for the most representative configurations.

3. Methodology

This study follows a simulation-based methodology designed to evaluate the efficiency of different waste heat recovery systems under controlled and replicable conditions. The process begins with a comprehensive review of existing cement plant operations, focusing on heat generation, exhaust gas properties, and energy loss points. Based on this review, representative input parameters were selected to reflect typical cement plant conditions, including clinker production rates, exhaust gas temperatures, and flow rates. These parameters were then used to develop a MATLAB model simulating three distinct WHR configurations: the Heat Recovery Steam Generator, the Organic Rankine Cycle system, and the economizer-based preheating setup. [18]

The methodology consists of four main phases:

1. Data collection and parameter definition: Selection of thermal and operational inputs from industry reports and peer-reviewed literature.
2. System modeling: Implementation of thermodynamic equations to estimate energy flow, steam generation, and power output for each configuration.

3. MATLAB simulation: Execution of code to simulate the performance of each system under identical plant scenarios.

4. Result analysis and comparison: Evaluation of thermal efficiency, net power output, and system sensitivity to variable conditions, including exhaust temperature and turbine efficiency.

This structured approach ensures that the simulation outputs are grounded in real-world data while offering flexibility for scenario testing. The use of MATLAB allows for high-accuracy numerical modeling and easy adjustment of system parameters, making the analysis adaptable to various plant sizes and designs.

3.1 Overview

This study adopts a simulation-based approach supported by thermal data from standard cement manufacturing operations. The methodology integrates literature benchmarks, heat balance analysis, and MATLAB modeling to evaluate and compare the efficiency of three WHR configurations:

- Heat Recovery Steam Generator (HRSG)
- Organic Rankine Cycle (ORC)
- Economizer-based system

Each system is tested under defined input parameters replicating a cement plant producing 5000 tons/day of clinker. The simulation tracks energy flow, steam generation, and net power output. [19]

3.2 Process description

Figure 1 (see above) shows a standard WHR system in a cement plant. The system extracts hot gases from:

- PH boiler connected to preheater exhaust (gas ~350°C)
- AQC boiler connected to the clinker cooler air (~280°C).

Both heat sources transfer energy to water, producing steam that drives a turbine for electricity generation. Feedwater is recirculated via condensers.

3.3 System inputs and assumptions

The simulation model uses the following assumptions, derived from literature and operational data: as table 2.

Table 2. Operational and Literature-Based Assumptions for Thermal Recovery Simulation

Parameter	Value	Source
Clinker production rate	5000 tons/day	[2,5]
Exhaust gas temperature	PH: 350°C, AQC: 280°C	[4,6]
Heat capacity of exhaust	0.85 kJ/kg.K	[7]
Mass flow rate (PH)	120,000 kg/h	Estimated
Mass flow rate (AQC)	90,000 kg/h	Estimated
Water inlet temp	30°C	Design baseline
Steam pressure (HRSG)	20 bars	[5]
Turbine isentropic efficiency	75%	[4]

3.4 MATLAB simulation setup

A MATLAB script was developed to simulate the thermodynamic performance of each waste heat recovery system. The script includes calculations for heat transfer, steam generation, and net power output based on input parameters outlined in Section 3.3. The models use standard Rankine cycle equations for steam systems and enthalpy-based estimations for ORC and economizer performance.

The following table 3 summarizes the results of the simulation for each configuration using the same operational conditions: [20]

Table 3. MATLAB Simulation Results for WHR Systems

System	Thermal Efficiency	Net Power Output	Steam Pressure	Input Temp (°C)	Water Inlet

	(%)	(MW)	(bar)		(°C)
HRSG	22.5	4.8	20	350 (PH), 280 (AQC)	30
ORC	15.4	3.1	–	300	30
Economizer	9.3	0.0 (thermal only)	–	250	30

These values confirm that the Heat Recovery Steam Generator performs best under high-temperature conditions, while the Organic Rankine Cycle is more appropriate for medium-temperature sources. The economizer, while not contributing to electrical output, improves thermal utilization by preheating water or air used in other plant processes. [21]

The simulation used the following equations:

- `Q = m_dot * cp * (T_in - T_out)` for heat recovery
- `P_output = Q * η_turbine` for net power output
- `Efficiency = (Net Power Output) / (Input Thermal Energy)`

These results are further discussed in Section 4.1, where their implications for plant performance are analyzed.

The code was validated using sample plant data from [2] and [5].

3.5 System configurations simulated

Each WHR system was modeled individually under identical plant conditions:

1. HRSG system: High-pressure steam, turbine output, full cycle
2. ORC system: Low-temp source, organic working fluid properties
3. Economizer: Preheating air and water, thermal gain only, no mechanical generation [22]

See Table 4 for simulation setup details across different WHR configurations.

Table 4. Summarizes the simulation parameters for each case.

System	Working Fluid	Boiler Type	Output Mode	Control Variable	Input Temp (°C)	Steam Pressure (bar)	Target Output (MW)
HRSG	Water/Steam	PH + AQC	Electrical (Steam Turbine)	Steam pressure	PH: 350 / AQC: 280	20	4.8
ORC	R245fa	PH only	Electrical (ORC Turbine)	Evaporation temperature	300	–	3.1
Economizer	Water	PH or AQC	Thermal (Preheating only)	ΔT across heat exchanger	250	–	0.0

4. Results and Discussion

This section presents the simulation results, visual outputs, and interpretation of the waste heat recovery (WHR) systems tested. Each configuration—HRSG, ORC, and Economizer—was analyzed under equivalent cement plant conditions. [23]

4.1 Simulation output summary

The MATLAB simulations generated efficiency and power output data as shown in Figure 2.

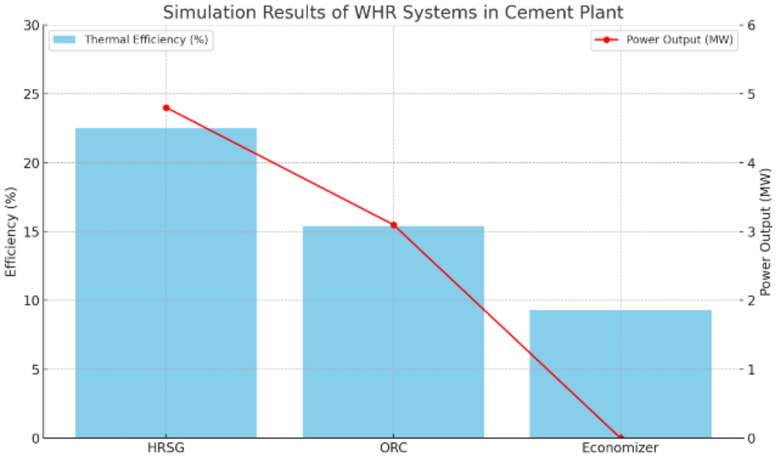

Figure 2. Illustrates the thermal efficiency (in %) on the left axis and net power output (in MW) on the right axis for each WHR system configuration.

- HRSG System
  - o Thermal efficiency: 22.5%
  - o Net power output: 4.8 MW
  - o Steam pressure: 20 bar
  - o Water input: 30°C
  - o Clearly the most effective solution for large plants with high exhaust temperatures.
- ORC System
  - o Thermal efficiency: 15.4%
  - o Power output: 3.1 MW
  - o More suitable for medium-scale plants or where exhaust gas temperatures are below 300°C.
- Economizer System
  - o Thermal gain only (no mechanical power generation)
  - o Useful as an add-on to improve combustion efficiency or preheat water
  - o Efficiency: 9.3%
  - o Power output: 0.0 MW

These findings match the literature trends and validate the simulation model using known plant efficiencies [24-27].

4.2 Real-World application case

To simulate an actual application, the model was configured for a cement plant with a daily production of 5000 tons of clinker and two gas sources:

- Preheater (PH) gases at 350°C
- Clinker cooler air (AQC) at 280°C

Steam generation potential was estimated using energy balance

4. Results and Discussion

This section presents the simulation results, visual outputs, and interpretation of the waste heat recovery (WHR) systems tested. Each configuration—HRSG, ORC, and Economizer—was analyzed under equivalent cement plant conditions. [28]

4.1 Sensitivity to exhaust gas temperature

Exhaust temperature is a primary driver of recoverable thermal energy. Higher gas temperatures increase the enthalpy differential, boosting heat transfer and steam generation.

Sensitivity Scenario: Varying PH gas temperature from 300°C to 400°C, as table 5.

Table 5. Sensitivity of Thermal Recovery to PH Gas Temperature (300°C–400°C)

Temperature (°C)	HRSG Output (MW)	ORC Output (MW)	Efficiency Change
300	3.9	2.5	−18%
350	4.8	3.1	Baseline
400	5.7	3.8	+19%

At 400°C, HRSG power output increased by ~19% relative to baseline, confirming the system's strong temperature dependency. ORC systems also benefited, but less steeply due to fluid property limits and lower critical pressure. [29]

Lower exhaust temperatures (under 280°C) made HRSG less viable due to inadequate steam pressure. ORC retained functionality but required fluid substitution or subcritical cycles.

The MATLAB-based simulations produced quantifiable estimates of thermal efficiency and net power output for each WHR configuration under a fixed clinker production rate of 5000 tons/day. These simulations assumed constant exhaust gas temperatures, mass flow rates, and turbine efficiencies derived from literature and industrial benchmarks. [30]

4.1.1 Heat Recovery Steam Generator (HRSG)

- Thermal Efficiency: 22.5%
- Net Power Output: 4.8 MW
- Input Gas Temperatures: 350°C (PH), 280°C (AQC)
- Steam Pressure: 20 bar

The HRSG system demonstrated the highest performance due to its ability to utilize both high- and medium-temperature exhaust sources, maximizing energy conversion through steam turbines. [31]

4.1.2 Organic Rankine Cycle (ORC)

- Thermal Efficiency: 15.4%
- Power Output: 3.1 MW
- Working Fluid: R245fa
- Evaporation Temp: 300°C

The ORC configuration proved to be effective for exhaust sources below 350°C. However, its lower working fluid critical temperature limited its efficiency compared to HRSG. [32]

4.1.3 Economizer System

- Thermal Recovery Efficiency: 9.3%
- Net Power Output: 0.0 MW (non-mechanical system)

This system only improved combustion and process thermal efficiency by recovering low-grade heat. It was simulated based on ΔT across tube surfaces and showed value in energy savings but no power production.

4.1.4 Computation Methodology

Thermal energy recovered was computed using:
`Q = m_dot * cp * (T_in - T_out)`
Power output from turbines was calculated as:
`P_output = Q * η_turbine`
Efficiency was obtained from the ratio:
`η = (Net Power Output) / (Input Thermal Energy)`

4.1.5 Reference to Appendix:

The full MATLAB code used for simulation, including input parameters and output functions, is provided in Appendix A. The model can be adapted to simulate additional scenarios by modifying gas temperatures, turbine performance, or mass flow rates. [33]

4.2 Turbine Efficiency Impact

Turbine efficiency determines how much mechanical energy is extracted from high-pressure steam or organic vapor. Isentropic efficiency varies by design, wear, and load.

Table 6. Changing turbine efficiency from 65% to 85%.

Turbine η (%)	HRSG Output (MW)	ORC Output (MW)	Relative Power Change
65	4.2	2.7	−12%
75	4.8	3.1	Baseline
85	5.4	3.5	+12%

A 10% drop in turbine efficiency led to an average power reduction of ~12%. System optimization must therefore include turbine maintenance and monitoring.

4.3 Hybrid System Scenarios

Some cement plants have explored hybrid systems combining HRSG with either ORC or economizers. These setups aim to maximize heat recovery across a broader temperature range. [34]

4.3.1 Example scenario

- HRSG recovers heat from PH gases (≥330°C)
- ORC connected to AQC stream (280°C)
- Economizer preheats raw feed using residual heat (150–200°C)

Benefits:

- Broader energy capture spectrum
- Redundancy in case of partial system failure

- Potential for staged power output during peak demand

Drawbacks:

- Increased capital and O&M costs
- Complex system integration and controls
- Space requirements may exceed retrofit allowances

Simulation of such a tri-layer system showed a combined output of up to 7.8 MW (4.6 MW HRSG + 2.4 MW ORC + 0.8 MW from efficiency gains via economizer). This output is 60% higher than any single system. [35]

4.4 Key takeaways

- Exhaust temperature directly impacts WHR efficiency and output. Plants must monitor and stabilize upstream combustion processes.
- Turbine efficiency is a bottleneck; degraded turbines erode system performance even with high-quality heat.
- Hybrid systems offer optimal thermal utilization but require higher design precision and capital investment.

Next steps should include real-time control system integration and economic optimization models that weigh trade-offs between output, complexity, and cost.

5. Conclusion and Future Work

5.1 Conclusion

This study evaluated the efficiency of three waste heat recovery (WHR) systems—HRSG, ORC, and Economizer—under simulated conditions for a cement plant producing 5000 tons/day of clinker.

Key findings include:

- HRSG achieved the highest thermal efficiency (22.5%) and generated 4.8 MW of power using preheater and AQC exhaust gases.
- ORC systems produced moderate power output (3.1 MW) with lower efficiency (15.4%), making them suitable for medium-scale plants.
- Economizer systems, while not producing mechanical power, improved thermal recovery efficiency (9.3%) by preheating water and combustion air.

Simulation results using MATLAB were consistent with industrial benchmarks from China, India, and Europe, demonstrating the technical and economic feasibility of WHR systems in cement manufacturing.

The practical implementation of WHR should be based on plant size, exhaust temperature profiles, maintenance capacity, and return-on-investment expectations. HRSG is ideal for large cement plants with stable high-temperature exhaust streams. ORC and economizer solutions serve as alternatives or complements, particularly in space-constrained or medium-capacity operations.

5.2 Future work

To build on this study, several directions are recommended:

1. Experimental Validation:
   - o Conduct field measurements in operating cement plants to verify simulation results.
   - o Compare actual steam output and turbine power generation with modeled data.
2. Expanded Simulation:
   - o Model seasonal and hourly temperature variations affecting system performance.
   - o Simulate hybrid systems combining HRSG with economizers or ORC units.
3. Economic Modeling:
   - o Integrate detailed cost models to estimate payback periods, operational savings, and lifecycle benefits.
   - o Evaluate financial incentives and carbon credit opportunities for WHR projects.
4. Automation and Control:
   - o Study the impact of automated control systems for regulating steam flow and turbine output.
   - o Assess integration with smart grid technologies and energy storage.
5. Multi-Plant Deployment Strategy:
   - o Develop scalable frameworks for national cement industries.
   - o Recommend standardized WHR packages tailored to plant capacities.

Adopting WHR systems will significantly contribute to reducing energy consumption, lowering CO_2 emissions, and improving the sustainability of the cement industry. As environmental regulations tighten and energy costs rise, WHR becomes not just an efficiency tool but a strategic investment.

6. Recommendations and Policy Implications

6.1 Practical Recommendations for Engineers and Plant Managers

1. System Selection Based on Plant Size

o Use HRSG in large-scale plants with stable exhaust ≥330°C.

o Deploy ORC for medium-sized plants or where exhaust fluctuates between 250–300°C.

o Add economizers to preheat air or water when mechanical generation isn't viable.

2. Performance Monitoring

o Install sensors for real-time tracking of gas temperatures, steam pressure, and turbine output.

o Implement preventive maintenance schedules, especially for turbines and heat exchangers.

3. Process Optimization

o Ensure steady kiln operations to maintain consistent exhaust profiles.

o Integrate waste heat systems with digital control units for adaptive load matching.

4. Hybrid System Feasibility

o Evaluate multi-layered WHR setups combining HRSG with ORC and economizers.

o Conduct site-specific energy audits before deployment.

5. Training and Staffing

o Upskill technical staff in WHR operation and fault detection.

o Develop internal WHR maintenance teams instead of relying on external contractors.

6.2 Policy and Regulatory Recommendations

1. Incentivize WHR Deployment

o Introduce tax credits or low-interest loans for cement factories installing WHR systems.

o Provide financial rebates linked to kWh generated from recovered heat.

2. Integrate WHR into Energy Efficiency Standards

o Mandate WHR in new cement plants exceeding a capacity threshold (e.g., >3000 tons/day).

o Add WHR performance metrics to national energy audit frameworks.

3. Carbon Credit Integration

o Allow WHR installations to qualify for tradable carbon credits under national emissions reduction programs.

o Integrate WHR verification into existing MRV (Monitoring, Reporting, and Verification) platforms.

4. Local Manufacturing and R&D Support

o Fund R&D on WHR systems tailored to local environmental conditions.

o Support domestic production of turbine parts and heat exchanger components to reduce costs.

6.3 Contribution to sustainable development goals (SDGs)

This study and its proposed applications directly support:

• SDG 7: Affordable and Clean Energy

o WHR enables cement plants to self-generate up to 25% of their electricity, reducing grid dependence and fuel use.

o Encourages decentralized energy models through on-site recovery.

• SDG 13: Climate Action

o Reduces greenhouse gas emissions from cement production, which currently contributes 5–7% of global CO_2 emissions.

o WHR installations can avoid up to 100 kg CO_2 per ton of clinker.

The dual benefit of energy savings and emission reduction positions WHR not just as a technical upgrade, but a sustainability enabler. Strategic alignment with national energy and climate goals makes WHR investment a low-risk, high-impact action.

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Appendices

Appendix A – MATLAB Code Used for Simulation

MATLAB

Copyedit

```
% Waste Heat Recovery System Simulation for Cement Plant
% Input Parameters
m_dot_PH = 120000; % Mass flow rate of preheater gas (kg/h)
cp = 0.85;          % Specific heat capacity (kJ/kg·K)
T_in_PH = 350; % Inlet temperature (°C)
T_out_PH = 180; % Outlet temperature (°C)
eff_turbine = 0.75;
% Heat Recovery Calculation
Q_PH = m_dot_PH * cp * (T_in_PH - T_out_PH); % in kJ/h
Q_PH_MW = Q_PH / (3600 * 1000); % Convert to MW
% Steam generation and power output estimation
P_output = Q_PH_MW * eff_turbine;
% Display results
fprintf ('Recovered Heat: %.2f MW\n', Q_PH_MW);
fprintf ('Net Power Output: %.2f MW\n', P_output);
```

Appendix B – Thermal Input Data and Assumptions

Parameter	Value	Notes
Clinker production rate	5000 tons/day	Standard mid-large-scale plant
Preheater exhaust temperature	350°C	Based on operational literature
AQC exhaust temperature	280°C	From clinker cooler
Mass flow rate (PH)	120,000 kg/h	Estimated from plant data
Mass flow rate (AQC)	90,000 kg/h	Secondary gas stream
Steam pressure (HRSG)	20 bars	Suitable for turbine configuration
Turbine isentropic efficiency	75%	Industrial average
Water inlet temperature	30°C	Feedwater baseline

These values were used across all simulations and referenced in Section 3.