Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/BA08.20250339
Published: December 20, 2025

Waste Heat Recovery Systems in Thermal Power Plants: Technologies, Efficiency, Eco-consciousness and Sustainability

Mohammed Monimu Aban Haque, Hasibul Ahsan Abdullah and Mohammed Mohsiu Naban Haque
Department of Mechatronics Engineering
World University of Bangladesh, Dhaka, Bangladesh
1125661855@student.wub.edu.bd

Abstract

Thermal power plants waste significant amounts of energy in the form of heat, leading to major issues related to efficiency loss and environmental degradation. This energy loss is known as waste heat. Waste Heat Recovery (WHR) systems provide a practical way to capture this unused heat and convert it back into useful power or process heat. By doing this, power plants become more efficient and significantly reduce harmful emissions. This review focuses on the main WHR technologies used in thermal power plants. Various methods are employed, such as standard heat exchangers, the Organic Rankine Cycle (ORC), the Kalina cycle, and newer systems that use supercritical CO_2. In this article, the system is evaluated by determining its efficiency through thermodynamic analysis. It also considers whether technology is affordable in terms of economic factors. Additionally, WHR helps control emissions caused by waste heat from power plants. By recovering waste heat, we can reduce global warming, which is a critical issue to address to ensure a safe environment. Finally, there are promising future directions, such as using thermoelectric generators (devices that turn heat directly into electricity) and advanced methods like AI-based optimization. Overall, this paper shows that recovering waste heat is essential for cutting costs, saving energy, and making thermal power generation more sustainable.

Keywords

Waste Heat Recovery (WHR), Thermal Power Plants, Organic Rankine Cycle (ORC), Thermodynamic Performance Analysis, Sustainability.

1. Introduction

Thermal power plants are important sources of electricity, especially in developing countries. But their thermal efficiency is low, as they convert only about 30–45% of fuel energy into electricity and lose the rest as waste heat. Improving efficiency is necessary because it can reduce fuel use, lower costs, and decrease greenhouse gas emissions. Studies also show that a huge amount of recoverable thermal energy is wasted every year, which highlights the importance of waste heat recovery for better energy security and environmental protection.

Waste heat in thermal power plants is the unused thermal energy released into the environment through flue gas, exhaust steam, cooling water, and equipment losses. Stated differently, it is the thermal energy produced by the plant that is not used to carry out beneficial tasks or supply downstream processes. High-temperature flue gases, turbine exhaust steam, and condenser cooling streams are the main sources of waste heat in thermal plants, according to research that categorizes waste heat by temperature levels and source types. Deploying suitable waste heat recovery (WHR) systems that are suited to the temperature regime and flow characteristics of the waste stream requires an understanding of these sources.

Unrecovered waste energy has significant negative effects on the environment and the economy. Environmentally speaking, when waste heat is released rather being used, more fuel must be used to maintain output, which increases emissions of CO2 and other pollutants. According to one study, even a 0.1% increase in large combustion power plant efficiency might result in a 1,000–1,500 tons annual decrease in CO_2 emissions (Zhao et al., 2020). Furthermore, thermal pollution caused by high discharge temperatures can harm ecosystems and lower the quality of water bodies. In terms of the economy, wasted energy is a lost chance that results in increased fuel costs, decreased profitability, and reduced competitiveness. However, research shows that by recovering waste heat, for example, when a combined system improved net power output by 18.11% and net thermal efficiency by 8.11%—the economic returns (higher power output, lower fuel cost) can be significant.

In light of this, the following topics will be covered in order in this review: the significance of energy efficiency in thermal power plants; the definition, categorization, and primary sources of waste heat; and the financial and environmental consequences of not recovering this energy. After that, the paper will discuss different WHR technologies, their performance in power plants, and their impact on sustainability.

2. Classification of Waste Heat and Major Heat Loss Points in Thermal Power Plants

Waste heat can be classified into high, medium, and low grades depending on its temperature. Waste heat is energy from power plants or industries that isn't used for work. High-grade heat (>400 °C) comes from boiler flue gases or turbines, medium-grade (230–650 °C) from flue gases and turbine exhausts, and low-grade (<230 °C) from cooling water or blowdown streams. High-grade heat can be converted to energy, while low-grade heat is mostly used for heating.

Waste heat losses in thermal power plants are mostly caused by a few key components. Boilers lose heat by convection, radiation, blowdown, and flue gas exhaust. According to studies, a large amount of boiler energy loss resulting from high-temperature exhaust not being fully utilized can be attributed to flue gas alone. Heat rejected to condensers and exhaust steam, which leaves the turbine at temperatures too low to carry out further mechanical work effectively, are two ways that steam turbines contribute to waste heat. According to research, condenser heat rejection can be responsible for more than half of all energy losses in some facilities.

Another significant source of heat loss is stack losses or flue gas exhaust. A significant amount of the energy from high-temperature flue gases is discharged into the atmosphere even with contemporary emission controls. For example, without recovery devices, up to 60% of the fuel energy in coal-fired thermal power plants may be lost as hot exhaust gases. Lastly, further small but cumulative heat losses throughout the plant are caused by auxiliary systems including pumps, compressors, and cooling circuits.

Emerging low-grade waste heat recovery methods include solid-state approaches such as reverse magnetocaloric systems, which show potential for improving efficiency at low temperatures (Kishore and Priya, 2017).

In the diagram shown above, it is shown that before the implementation of WHR system, there was no recovered exergy. But after applying such technology waste heat is recovered as recovered energy, although e amount of recovered exergy is always less than or equal to the amount of recovered energy (heat) and depends heavily on the temperature (quality) of the heat source. Efficient WHR systems use heat loss locations to guide design. Low-grade heat suits heating or preheating, while high-grade heat from flue gases or turbines can generate electricity or support industrial processes. To increase overall plant efficiency and optimize the financial and environmental advantages of WHR implementation, it is essential to comprehend these differences. Below there is shown a small Table 1 describing heat grade and recoverable technology.

Table 1. Heat grade and temperature ranges

Heat Grade	Temperature Range (°C)	Typical Source	Recoverable Technology
High	>400	Flue gas, turbine exhaust	Steam Rankine Cycle, Kalina Cycle
Medium	200-400	Turbine casing, superheater bypass	Organic Rankine Cycle (ORC), Heat Exchangers

Low	<200	Cooling water, condenser	Thermoelectric Generators (TEGs), Heat Pumps

3. Need for Waste Heat Recovery (WHR): Energy Saving Potential, Role in Sustainability, and Emission Reduction

Installing Waste Heat Recovery (WHR) systems in thermal power plants is now a crucial tactic for improving energy efficiency and accomplishing sustainable development. Conventional thermal systems lose a large amount of their energy as waste heat through flue gases, exhaust steam, and condenser cooling water, which results in inefficiencies and environmental problems. Research shows that approximately 60% of the fuel energy intake can be lost as thermal energy that isn't used, especially in boilers and condensers, recovering even a small portion of this waste heat can significantly increase the plant's overall thermal efficiency, reduce its specific fuel consumption, and prolong the life of its current energy resources.

From an energy-saving standpoint, WHR technologies enable the transformation of heat that would otherwise be lost into beneficial activities, including district heating, electricity generation, or feedwater preheating. For instance, boiler fuel consumption can be decreased by using flue gas heat for regenerative feedwater heating, and medium-grade waste heat can be transformed into extra electrical output via organic Rankine cycle (ORC) systems. Depending on the configuration and quality of recoverable heat, research indicates that successful WHR integration can boost plant efficiency by 5–10%. By lowering reliance on fossil fuel imports, these advancements directly result in reduced operational costs and improved energy security.

WHR systems are essential tools for environmental and emission reduction in addition to saving energy. WHR reduces the fuel needed for the same output by making better use of available energy, which lowers emissions like CO_2, SO_2, and NO_2. This leads to cleaner production and less environmental impact. Chen et al. (2022) also showed that WHR improves energy use and reduces carbon intensity, supporting global carbon-neutral goals.

WHR also supports sustainability by promoting circular energy use in industrial systems. Instead of wasting heat, the energy is reused for secondary processes, reducing resource use and thermal pollution. This circular approach strengthens the economic resilience of power plants and supports SDGs 7 and 13.

Integrated tri-generation systems combining cogeneration and solar cooling have demonstrated improved overall efficiency and reduced emissions in thermal systems.

Using WHR technology in thermal power plants helps improve efficiency, save fuel, cut emissions, and protect the environment. The graph below shows distribution of global waste heat recovery potential by sector, where power and steam generation accounts the largest share of recoverable potential, appearing to be around 47%, then there is the oil and gas/petroleum refining industries accounts for significant portion 25%, next the chemical and petrochemical sector accounts for only 15%, lastly the cement, steel and others only accounts for 13%. The integration of waste heat recovery between cement plants and coal-fired power plants has been shown to significantly improve overall system efficiency and utilization of industrial waste heat (Heng et al., 2025.).

The combination of these results strengthens WHR's position as a key component of sustainable energy management and a vital route to producing low-carbon electricity in the contemporary industrial period (Figure 1).

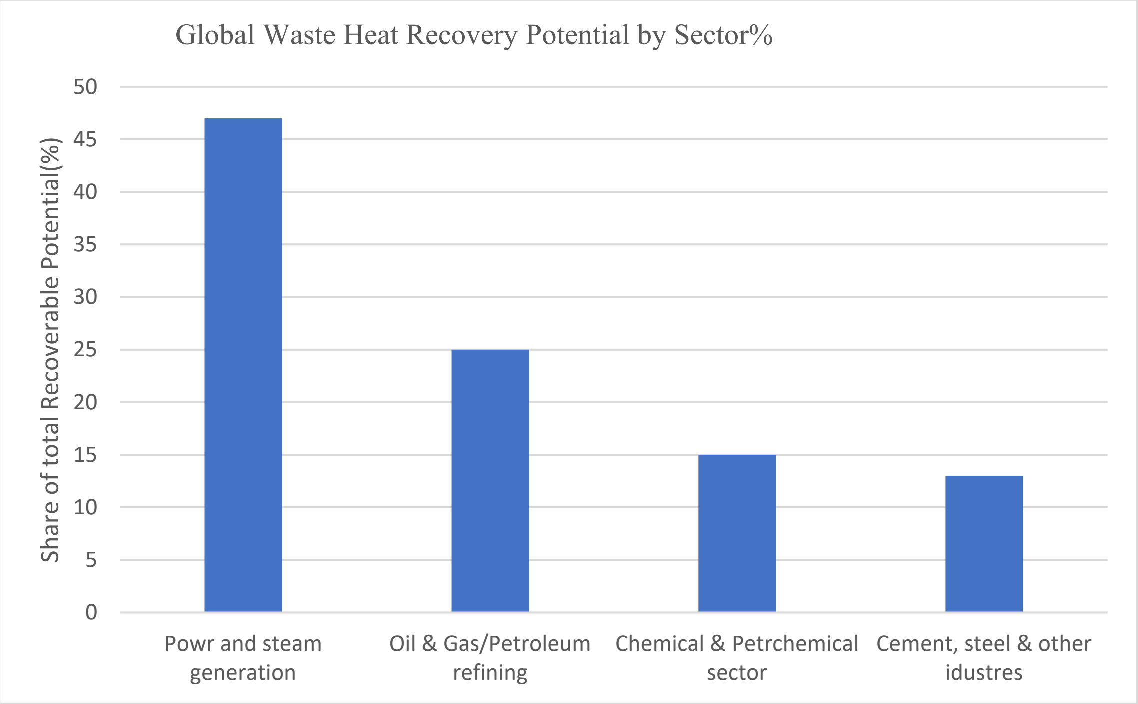

Figure 1: Global Waste Heat Recovery Potential graph

4. **Technologies and Performance**

Conventional Technologies

Conventional WHR technologies transfer heat from hot waste streams to cooler fluids like water or air without changing their phase. They help improve a plant's energy efficiency by reducing wasted heat (Table 2)

Table 2. Recuperative and Regenerative Heat Exchangers

Technology	Principle	Application in WHR
Recuperative Heat Exchangers	The hot and cold fluids flow continuously through separate channels (e.g., tube-and-shell, plate exchangers), transferring heat through a separating wall.	Used for continuous heat transfer from flue gas to boiler feed water, or to preheat combustion air. They are simple, reliable, and have no moving parts.
Regenerative Heat Exchangers	Heat is transferred intermittently. A porous solid matrix first absorbs heat from the hot fluid, and then the flow is switched, and the matrix releases that stored heat to the cold fluid.	Primarily used in high-temperature applications where the heat source is intermittent or where the waste stream is dirty. This includes rotating wheel regenerators or fixed matrix systems.

Economizers and Air Preheaters
These technologies are highly effective, where recuperators integrated directly into the boiler's flue gas path. Like shown in Figure 2.

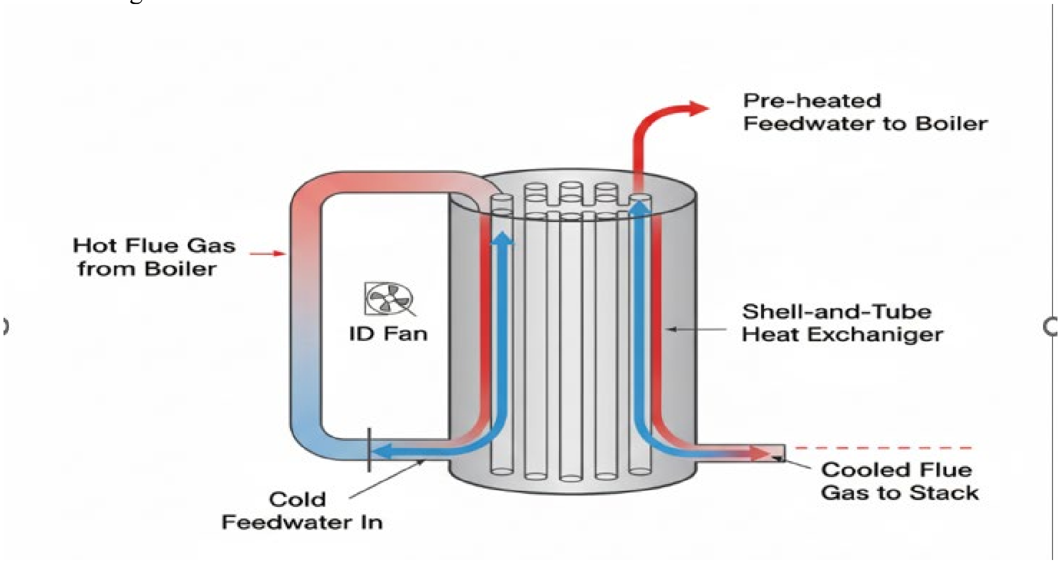

Figure 2. Schematic of heat exchanger and boiler

Economizers: These heat exchangers take heat from low-temperature flue gas to preheat boiler feed water, reducing fuel use and improving the plant's thermal efficiency.

Air Preheaters (APH): These systems use waste heat to preheat the combustion air, raising the temperature in the boiler. This improves heat transfer, burns fuel more completely, and reduces energy losses.

5. Advanced Thermodynamic Cycles

While conventional technologies improve plant efficiency by preheating inputs, advanced thermodynamic cycles use the recovered heat to generate additional power that otherwise would be entirely wasted. These cycles are critical for converting low- to medium-grade heat sources into valuable electricity.

Organic Rankine Cycle (ORC)
The ORC is essentially a standard Rankine cycle that uses a high-molecular-mass organic fluid (like refrigerants or hydrocarbons) instead of water/steam.

Mechanism: Due to the lower boiling point of organic fluids, the ORC can efficiently recover heat from low-grade sources (typically 80°C to 300°C). The fluid vaporizes, drives a turbine to generate electricity, condenses, and is pumped back into the evaporator.

Performance: The ORC has high thermal efficiency for its low-temperature inputs and excellent turbine efficiency due to the heavy molecular mass of the working fluids. It is the most commercially mature technology for converting low-grade heat into power. The selection of the working fluid is paramount, as noted in the source material, to maximize exergy recovery and minimize environmental impact.

Kalina Cycle
The Kalina Cycle is a variant of the Rankine cycle that uses a binary working fluid, typically a mixture of water and ammonia.

Mechanism: The mixture allows for a varying boiling temperature during the heat input process (a non-isothermal phase change). This temperature gliding closely matches the cooling curve of the waste heat source, minimizing the temperature difference (ΔT) between the hot source and the working fluid during heat transfer.

Performance: By minimizing ΔT, the Kalina Cycle drastically reduces irreversibility (exergy destruction) in the boiler/evaporator, making it theoretically more exergetically efficient than a pure-substance Rankine cycle for certain heat sources.

Supercritical CO_2 Systems (s-CO_2)
The s-CO_2 cycle uses carbon dioxide as the working fluid, operating above its critical pressure (7.38 MPa) and often above its critical temperature (31.1°C).

Mechanism: Operating in the supercritical phase significantly increases the density of the CO_2, making the turbomachinery much smaller (up to 10-100 times smaller than steam turbines) for the same power output.

Performance: s-CO_2 offers extremely higher power density and can operate efficiently at high temperatures (up to 700°C). It is still in development for WHR but promises high thermal efficiency and compact plant footprints, making it ideal for future high-temperature waste streams.

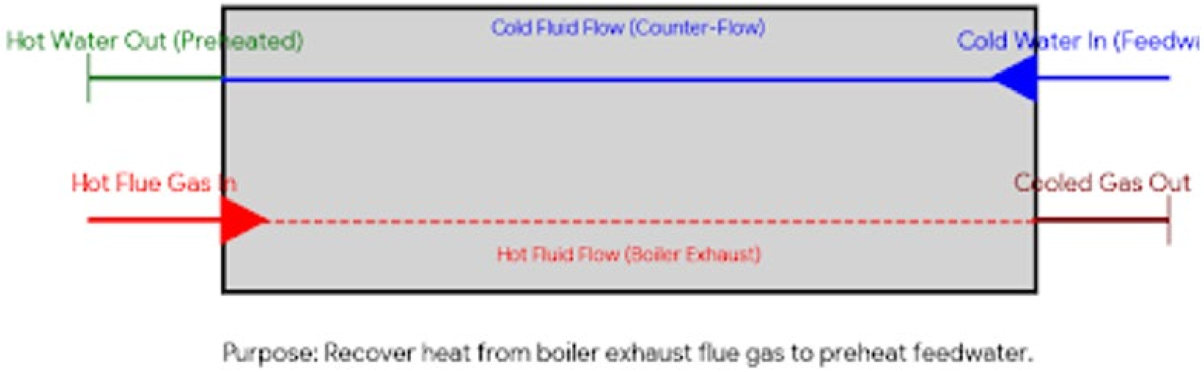

Figure 3: Schematic of a Typical Counter-Flow Heat Exchanger for WHR (Ecnomizer)

As shown in Figure 3, an economizer used for waste heat recovery. Here hot flue gas enters one side and exits as cooled gas, while cold water enters the opposite side and exits as hot preheated water. It is used to improve efficiency by preheating incoming cold water using waste heat from hot flue gas (Table 3).

Table 3. Working fluids

Cycle Type	Working Fluid	Temperature Range °C	Typical Efficiency (Super%)	Advantages	Limitations
Organic Rankine Cycle (ORC)	R245fa, Toluene, Cyclopentane, etc.	80–350	8–15	Simple design; utilizes low-grade heat; compact system.	Lower power output; efficiency is highly sensitive to fluid selection.
Kalina Cycle	Ammonia-Water Mixture	100–500	10–20	Higher efficiency than basic ORC due to non-isothermal phase change.	More complex system design and control; toxicity/pressure concerns with ammonia.
Supercritical CO_2(sCO_2) Brayton Cycle	Carbon Dioxide (CO_2)	>250	20–30	Very high efficiency at medium-to-high temperatures; highly compact turbomachinery.	Requires high operating pressure (up to 30 MPa); complexity of critical point operation.

6. Performance Analysis

Energy and Exergy Efficiency The core difference between the First and Second Laws, as noted in the provided text, is critical here:

Energy (First Law) Efficiency: This is the basic thermal efficiency, measuring the ratio of the useful energy output (e.g., net electricity generated) to the total energy input (total heat absorbed). It indicates quantity and is essential for fuel consumption calculations.

Exergy (Second Law) Efficiency: This is the true measure of thermodynamic perfection, calculating the ratio of the actual work output to the maximum possible work output (change in exergy input). It is the most reliable measure of performance for WHR because it quantifies the useful work potential (Exergy) that is successfully captured, directly indicating the degree of irreversibility (lost opportunity) in the process. Maximizing it is the design objective for any advanced WHR cycle. (Moran and Shapiro, 2010).

Economic Feasibility and Cost–Benefit Analysis
A WHR project must prove its economic benefit over its
lifecycle. This analysis typically involves:

Capital Expenditure (CAPEX): Initial cost of equipment (heat exchangers, turbines, pumps, etc.). ORC equipment tends to have higher CAPEX than conventional heat recovery equipment.
Operational Expenditure (OPEX): Running costs, including maintenance, fluid replacement, and parasitic power consumption.

Revenue/Savings: Value of the recovered energy (electricity generated or fuel saved).

Payback Period (PBP): The time required for the cumulative revenue/savings to equal the CAPEX.
Net Present Value (NPV) & Internal Rate of Return (IRR): These standard financial metrics determine the profitability and long-term viability, considering the time value of money.

Key Economic Trade-off: Advanced cycles like ORC and Kalina offer higher energy output (greater revenue) but have higher CAPEX and complexity came to simple air preheaters, making the PBP a critical decision factor.

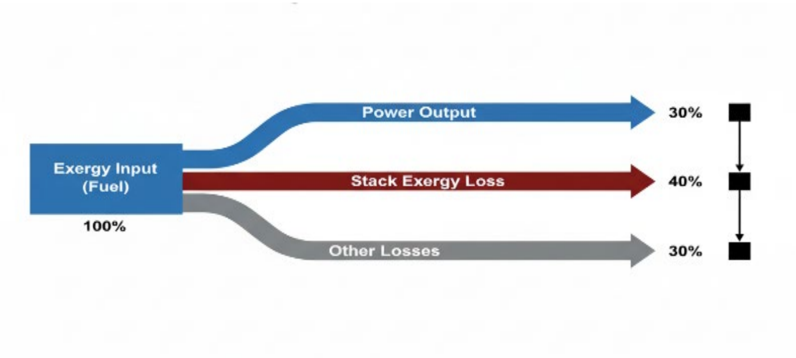

Figure 4: Exergy Flow diagram (before WHR integration)

The Figure 4 above shows an exergy flow diagram for a system before the integration WHR unit. It illustrates how the total exergy input from the fuel I distributed among the useful power output and various losses.

Real-world application validates performance metrics and economic viability:
Below on Figure 5, it explains the efficiency comparison different WHR cycle. For manifest understanding the process of using such cycles are also written here.

ORC: Widely deployed globally on stationary diesel engines, geothermal wells, and industrial waste heat (e.g., cement kilns). Typical ORC units range from 100 kWe to 10 MWe, often achieving 10-15% thermal efficiency (for the ORC itself) depending on the heat source temperature. They offer excellent operational stability with minimal operator intervention.

Kalina Cycle: Less widely adopted than ORC due to the complexities of handling the ammonia-water mixture. Success stories exist primarily in geothermal plants (where the heat source is often suitable for the temperature glide) and specific industrial applications. Applying the cycle can bring about 15-20% of thermal efficiency.

sCO_2 Brayton Cycle: It is a fundamental thermodynamic cycle that describes how gas turbine engines and jet engines operate. It is commonly used for both propulsion and power generation. With this cycle thermal efficiency can be achieved up to around 30% depending on the pressure ratio. Higher pressure ratios generally lead to higher efficiency. Conventional Systems: Economizers and APHs are standard in nearly all modern thermal power plants. They typically account for a 2-5% increase in the overall plant's First Law Efficiency, which translates to massive annual fuel savings. These case studies confirm that while conventional systems are cost-effective for efficiency improvements, advanced cycles are necessary to truly convert low-grade waste heat into revenue-generating electrical power.

7. Sustainability, Challenges, and Future Prospects

Waste Heat Recovery (WHR) is important for improving energy efficiency. WHR systems help reduce energy waste and support environmental sustainability.

Significant CO_2 Reduction By recovering heat that would otherwise be rejected and converting it into useful energy (electricity or heating), WHR directly reduces the demand for primary fuel sources (like coal or natural gas). This substitution capability the core mechanism for achieving substantial carbon dioxide (CO_2) and greenhouse gas (GHG) emission reductions—a central finding in the analysis of integrated systems like the coal-fired power plants reviewed.

Life Cycle Assessment (LCA) of WHR technologies cut the need for new or extra-running power plants, reducing emissions, resource use, and water consumption.

Enhanced Resource Efficiency WHR boosts energy efficiency, reduces fuel use, and helps conserve water by capturing vapor from flue gas.

Figure 5 represents the Reduction of CO_2 Emission with WHR integration". It compares the percentage of CO_2 emission reduction achievable through different waste heat recovery (WHR) integration methods. The highest reduction in CO_2 emissions is achieved by the Supercritical (sCO_2) Brayton Cycle, at approximately 40%. Medium Grade Heat integration results in a reduction of about 30%. Waste to boiler integration achieves around 25% reduction. Low pressure economizer and Thermoelectric Generators both result in the lowest reduction, at approximately 15% (Table 4).

Table 4. Cycle types and their efficiencies

Cycle Type	Working Fluid	Temperature Range (°C)	Typical Efficiency (%)	Advantages	Limitations
Organic Rankine Cycle (ORC)	R245fa, Toluene, Cyclopentane, etc.	80–350	8–15	Simple design, uses low-grade heat, compact system footprint.	Lower power output, fluid selection critical for efficiency.
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Thermoelectric Generators (TEGs)	Semiconductors Bi_2,Te_3, PbTe, etc.	100–1000	3–8	Solid-state (no moving parts), silent operation, highly reliable, scalable.	Low conversion efficiency, expensive material cost.

Despite its clear benefits, WHR faces several technical and economic hurdles that limit widespread implementation:
Technical Issues and Stream Quality:

Low-Grade Heat
A large portion of recoverable industrial waste heat is low-temperature (below 150°C), making its conversion into electricity less efficient and more costly with conventional technology.

Material and Corrosion
Flue gases often contain corrosive elements (e.g., sulfur compounds), particularly when the gas temperature drops near the dew point. This poses a major corrosion challenge for heat exchanger materials, demanding expensive, specialized components.

Intermittency and Fluctuation
The heat source in many industrial processes is often intermittent or highly variable in temperature and flow rate. This instability complicates system integration and optimization, impacting the reliability and lifespan of WHR equipment.
Economic and Operational Challenges

High Initial Investment The capital cost for installing WHR technologies (e.g., Organic Rankine Cycle units, specialized heat exchangers) can be high, leading to long payback periods that deter adoption, especially for Small and Medium-sized Enterprises (SMEs).

Lack of Suitable Heat Sink The successful application of WHR requires a nearby, economically viable use for the recovered energy (a heat sink). A mismatch between the heat source availability and the sink's demand often renders a WHR project infeasible.

Thermoeconomic Justification
As highlighted by Mousavi & Ameri (2018), a purely energy-based analysis can be misleading. A rigorous thermoeconomic and exergy analysis is essential to ensure the value of the recovered energy justifies the investment.

8. Future Developments

The future of WHR is defined by the integration of cutting-edge technologies and supportive policy frameworks, with recent studies outlining clear development pathways and long-term perspectives for waste heat recovery technologies (Huang, 2023).

Emerging Technologies
Supercritical CO_2(sCO_2) Brayton Cycle As highlighted by Yari et al. (2018), this cycle is promising for high-temperature WHR, offering high efficiency and system compactness.

Thermoelectric Generators (TEGs)
Nematollahi & Rahimi (2021) emphasize TEGs for their solid-state reliability and ability to convert heat directly into electricity, making them ideal for distributed or space-constrained applications, despite current limitations in cost and efficiency.

Hybrid Systems
Combining technologies like ORC with solar thermal or integrating multiple recovery stages (cascading) to utilize heat at different temperature levels will become standard to maximize overall efficiency.

Role of Digitalization and Policy

AI-Based Optimization Liu et al. (2023) underscore the transformative role of AI and Machine Learning (ML). AI can provide smart monitoring for predictive maintenance, real-time optimization of system parameters (flow rates, temperatures) to adapt to fluctuations, and predictive modeling to match heat supply with demand, maximizing energy conversion efficiency.

Policy Support
Supportive government policies, such as tax credits, carbon pricing mechanisms, and regulations that mandate minimum energy efficiency standards, are crucial to overcoming the economic barrier of high upfront costs and stimulating investment.

9. Conclusion

Waste Heat Recovery is a non-negotiable strategy for the global transition to sustainable energy systems. It simultaneously addresses energy security, economic competitiveness, and climate mitigation by tapping into vast, unused resources. The research reviewed confirms that technologies like sCO_2 cycles and advanced integrations for coal power plants are technically viable and offer substantial CO_2 reductions. However, technical challenges like corrosion and economic barriers related to capital cost and low-grade heat utilization persist. Prioritize R&D into highly efficient, cost-effective systems for low-temperature WHR (e.g., advanced ORC working, fluids, innovative thermoelectric materials). Intensify the development and commercialization of **AI and digital twins** for real-time WHR optimization and predictive maintenance to minimize operational risks and maximize ROI. Implement robust, stable government policies that recognize the environmental value of WHR, using mechanisms like feed-in tariffs or capital grants to bridge the initial investment gap.

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Biographies

Mohammed Monimu Aban Haque is a bachelor's student in the Department of Mechatronics Engineering at the World University of Bangladesh (WUB). His academic interests include thermal systems, waste heat recovery technologies, ordnance engineering, weapon system engineering, defense technology and automation. He has skills in arduino programing, basic cyber security, electrical fabrication in machines. He is currently engaged research focused on efficiency enhancement in thermal power plants.

Hasibul Ahsan Abdullah is a first-year undergraduate in Mechatronics Engineering at the World University of Bangladesh. His interests include waste heat recovery, energy efficiency, and thermo-fluid systems. He has skills in data analysis, Arduino, and C programming, and practical experience building an RC car and a line-following autonomous vehicle. He is expanding his knowledge in thermal sciences and energy technologies, with future research goals in renewable energy, thermal systems, and automation.

Mohammed Mohsiu Naban Haque is a bachelor's student studying Mechanical Engineering at the World University of Bangladesh (WUB). His interests include thermodynamics, power plant engineering, sustainable energy systems, ordnance engineering, weapon system engineering, and defense technology. He has skills in using workshop equipment, building small machineries and toys. He is currently exploring research related to performance improvement and energy efficiency in thermal power plants.