

# Waste Heat Recovery and Energy Reutilization Technologies in Industrial Processes: Research on Improving Energy Efficiency and Reducing Emissions

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**Abstract.** Industries are significant contributors to global energy consumption and greenhouse gas emissions, making energy efficiency improvements essential. WHR offers a valuable solution by capturing and reusing heat that would otherwise be lost, thus enhancing energy efficiency and reducing environmental impacts. This paper explores the application of WHR technologies across various industries, including steel, cement, and petrochemicals, where waste heat accounts for a large portion of energy losses. Technologies such as heat exchangers, ORC, and TEGs are discussed for their roles in converting waste heat into usable energy forms, such as electricity or heat for industrial processes. The review also covers advancements in materials and hybrid systems to optimize efficiency, as well as the potential of WHR in stabilizing renewable energy sources like solar and wind power. The integration of WHR systems into smart grids is highlighted as a future trend for improving energy management.

## 1 Introduction

To address environmental concerns, industries, as significant contributors to climate change, must take responsibility for reducing their environmental impact. In 2000, global energy consumption reached 10.3 million tons of oil equivalent (Mtoe) per year [1]. Research conducted in 2004 estimated that the technical potential for energy savings could be as high as 25–37 exajoules (EJ) per year [2], demonstrating that improving energy efficiency in industries could significantly reduce both energy consumption and environmental problems.

Waste heat recovery (WHR) is a crucial strategy for enhancing energy efficiency in the industrial sector. For instance, a 2017 study by Qi Zhang and his team in China found that 20%–50% of the energy used in the iron and steel industry—approximately 1 GW—was wasted in the form of heat [3]. Similarly, N.A. Madlool's 2011 research on cement manufacturing showed that 15.7% of energy consumption is associated with cement production, with developing countries wasting 50%–60% of that energy as heat at temperatures reaching 1500 °C [4]. In the food production sector, energy consumption accounts for 12%–15% of total industrial energy use, with most energy waste being thermal [5]. These examples illustrate that thermal energy represents the largest portion of waste in

many industries, making waste heat recovery a feasible and effective strategy for reducing energy losses.

Waste heat recovery is applied across various industries. A study conducted in Europe found that WHR is implemented in iron and steel manufacturing (with heat recovery potential of 11.4%), nonmetallic minerals (11.4%), textiles and leather (11.0%), chemical and petrochemical industries (11.0%), paper and pulp production (10.6%), nonferrous metals (9.6%), and other sectors (20.4%) [6]. The basic principle of WHR involves transferring heat from waste gases to fluids within heat exchangers, allowing the captured energy to be reused in industrial processes. Common WHR technologies include finned pipes, heat pipes, furnace regenerators, passive air preheaters, recuperative and regenerative burners, recuperators, rotary regenerators (heat wheels), shell-and-tube heat exchangers, and waste heat boilers [6].

This structured approach to waste heat recovery provides a practical solution for reducing energy waste and improving overall industrial efficiency.

## **2 Sources and classification of waste heat in industrial process in industrial processes**

To optimize waste heat recovery, it is essential to classify heat sources according to their temperature ranges and apply appropriate recovery methods for each class. Based on research conducted in Germany, heat sources can be broadly categorized into three temperature ranges: low temperature (below 100°C, primarily from steam and exhaust gases), medium temperature (100–400°C, mainly from drying and cooling processes), and high temperature (above 400°C, primarily from furnaces and boilers). Higher temperature sources offer greater potential for efficient heat recovery. However, when the temperature of the source falls below 200°C, it is generally considered insufficiently efficient for reuse, as the energy recovery potential is significantly reduced [7]. This classification is critical for designing and selecting the appropriate waste heat recovery technologies to maximize energy efficiency across different industrial applications.

The heat recovery technologies are mainly separated into two kinds, the direct and indirect. In the direct recovery method, the waste heat sources will be screen out by the heat exchangers or recuperators and then directly output back to the production line themselves or to other heat consuming industries. Besides, the indirect method, the waste heat is transformed to other forms such as electricity by thermoelectric generators or organic Rankine cycle (a more efficient way using waste heat resource).

From various industries, some of them have been defined as high potential industries for WHR. The steel and metal production, which has high heat potential can generate 1.25MW thermal energy in the standard in European countries [8]. At the same time, the waste heat production in the cement industries can reach 2725kw electricity with heat efficiency at 0.218 [9]. Besides, in another high heat potential industry that produce petrol or gas, the efficiency of the heat recovery is varied between single digit to 20%, in other words, a few MW of thermal energy can be reutilized in a manufacture pant consumes 100 MW thermal energy [10].

## **3 Technology for waste heat recovery and energy reutilization**

### **3.1 Heat exchangers and recuperators**

Waste heat treatments are broadly categorized into direct and indirect methods. In direct methods, waste heat is reused either within the industry or supplied to other heat-consuming

sectors. Indirect methods involve capturing waste heat and converting it into other forms of energy, such as electricity.

Heat exchangers play a critical role in indirect recovery methods, facilitating the transfer of heat from waste sources to other fluids. Common types of heat exchangers include shell and tube exchangers, and plate exchangers. Shell and tube exchangers consist of a cylindrical shell containing multiple tubes; as hot fluids pass through the tubes; heat is transferred to a cooler fluid circulating outside the tubes. Plate heat exchangers, on the other hand, use thin metal plates with large surface areas to enhance the heat transfer process. The greater surface area allows for more efficient heat capture and transfer, optimizing the recovery process.

### **3.2 Organic rankine cycle (ORC) systems**

The organic Rankine cycles (ORC) which are the improved technic of Rankine cycles that recycle the low-grade heat resources in the industries. With organic fluid with low boiling point in the system, the efficiency of ORC is larger than its prototype the Rankine cycles. In the paper industry, 10% to 15% of the waste heat have been recycled to electricity [11]. In the geothermal energy industries, the efficiencies can reach 12% to 20% [12]. From a review of ORC application in different industries, the efficiencies of the recycle were 8% to 18% [13].

### **3.3 Thermoelectric generators (TEGs)**

Thermoelectric generators (TEGs) represent another advanced technology for converting heat into electricity. These generators typically employ thermoelectric materials such as bismuth telluride for room temperature applications and lead telluride for high-temperature environments. TEGs are constructed using two types of semiconductors, p-type and n-type, connected in parallel. As heat flows from the hot side to the cold side, the temperature difference across the material drives the movement of electrons or holes, generating an electric current [14,15]. Recent advancements have introduced new materials like high-entropy alloys, organic compounds, nanowires, and nanoribbons into TEGs, further enhancing their efficiency. Additionally, improved energy management systems and performance optimization strategies have contributed to increased efficiency and overall effectiveness in energy conversion.

### **3.4 Heat pump and absorption chillers**

The heat pump and absorption chillers are also common in WHR in industries. Heat pumps can transfer the heat from cooler area to a warmer area, in industries, heat pumps are commonly applied to heating or drying process. In the food and beverage productions, the heat pumps are used to maintain the temperature during the food process and packaging. From the research to the efficiency of heat pumps in the food production, the coefficient of performance (COP), the standard to describe the efficiency of the heat pumps, is in the range of 3.0-5.0, that means by using 1 unit of electric power, the heat pumps can remove 3.0-5.0 units of heat from the environment [16] At the same time, heat pumps also reduce the heat waste in the drying and heating process of textile industry at the COP value 3.0-4.5 [17].

With similar working principle, the absorption chillers are applied to the pharmaceutical industry, with COP value at 0.6 to 0.9 [18].

Besides the normal industries, the heat pumps and absorption chillers are also applied to the space to ensure the crew comfort, recycle the waste heat and control the thermal energy. However, this system should be redesign because of the fluid in the heat pumps and chillers

runs motivated by the gravity, however, in the space microgravity and radiated environment, more protection and the motivation of fluid should be reconsidered.

## **4 Applications of waste heat recovery in industries**

### **4.1 Successful WHR implementations in steel industry**

For the WHR in many different industries, several of them are quite successful. The WHR in steel industries for example. In Turkey, the efficiency improvement of WHR system about 70% of the waste energy, and 15% to 30% of the total energy have saved. At the same time, it also reduces 10% to 20% of the CO<sub>2</sub> emission [19]. China, which takes huge amount of world steel production, WHR reaches 40% efficiency of the recovery of waste heat, or 25% of its energy consumption, to electricity or usable heat and 25% of its CO<sub>2</sub> emission has reduced [20]. For another example, in the UK, the WHR in steel industries has the efficiency around 50% to 60% of its waste heat or 20% to 35% of its total energy consumption. At the same time, 18% of its CO<sub>2</sub> pollution has reduced [21].

### **4.2 WHR in chemical and petrochemical industries**

In the chemical and petrochemical industries, the WHR has also improved the efficiency of energy usage. The researchers in Canada conclude that the WHR system can save around 15% to 30% of the total energy consumption with the efficiency around 60%. From the statistic, the costs on energy saving constructions can be payback in 2 to 5 years. At the same time, in Brazil, the WHR system has the efficiency at around 55% and saves 20% to 25% of its energy consumption [22]. In the economic analyzation, the costs can be reduced significantly, with the average return on investment (ROI) of around 3 to 4 years [23]. Meanwhile, the WHR in Chinese chemical and petrochemical industries has the largest efficiency that up to 70%, recovers 25% to 30% of the energy, and the cost can be paid back in 2 to 3 years [24].

### **4.3 WHR in cement and glass manufacturing**

In the cement and glass manufacturing, the WHR system is more complex than in the other industries mentioned previously. In Brazil, the plants use heat exchangers to capture the heat resources in the kiln exhausted gas and convert it into usable thermal energy or electricity. The efficiency of the recovery is up to 60%, and around 25% of the energy consumption can be reduced [25]. In South Korea, the WHR system in glass manufacturing is consist with heat exchanger and recovery boiler to convert heat in flue gas into available energy for preheating the materials and generate electricity. With efficiency up to 55%, 30% of the energy has recovered [26]. In Vietnam, the recovery system uses heat exchangers and regeneration burners to capture the heat source from kiln gases, improves the energy efficiency, reduces the reliance on external heat source. From the research, 20% to 35% of the energy in both industries has reduced and the efficiency is around 40% to 50% [27].

### **4.4 Cross-industry comparisons and best practice**

In successfully installing the WHR system to the various industries, some key factors are included. From the research around the world, a good WHR system has good system integration, which means the appropriate adoption to different heat resources and industry structure, financial incentives, which means the governments or nations give subsidies or

crucial encouragement to the WHR technologies, technology availability, which means that the WHR system should include stable, advanced and effective technologies [28,29].

Following the factors, the cement industry in India achieve 45% in the heat recovery by using pre-heaters and recovery boilers. Germany glass production has the system with average efficiency at 50% reduce 30% of the energy usage [30]. At the same time, the efficiency of steel industries in Japan, Petrochemical sector in Saudi Arabia, aluminum smelting industry in Australia and paper industry in Sweden, achieves 50% or more [31,32].

## 5 Future trends and research directions in waste heat recovery

With technological advancements, more efficient materials and solutions have emerged for WHR systems. In TEGs, new semiconductor materials with higher conversion rates are increasing efficiency. Additionally, hybrid WHR systems, which combine different recovery methods, can optimize performance by utilizing the remaining heat from other recovery solutions.

WHR systems are also proving beneficial in renewable energy generation. For example, using waste heat to preheat fluids or directly supply power can enhance the efficiency of solar power plants and biomass systems. WHR systems can further stabilize intermittent renewable sources like wind and solar energy, ensuring a more reliable energy output.

Furthermore, as smart grids become more established, WHR systems can be integrated into the grid to supplement electricity during peak demand hours. Excess electricity generated during low-demand periods can be stored and released as needed, improving grid efficiency.

Future improvements in WHR systems should focus on enhancing both efficiency and scalability. The development of new materials and innovative system designs will be crucial in pushing the boundaries of waste heat recovery technology.

## 6 Conclusion

In conclusion, WHR represents a significant opportunity for industries to enhance energy efficiency, reduce environmental impact, and contribute to global sustainability efforts. As demonstrated by various sectors, including steel, cement, chemical, and petrochemical industries, WHR systems can recover substantial amounts of energy, reduce operational costs, and lower greenhouse gas emissions. The successful implementation of WHR technologies, such as heat exchangers, organic Rankine cycles, and thermoelectric generators, has proven effective in converting waste heat into usable energy or electricity.

Advancements in materials, hybrid recovery systems, and smart grid integration further underscore the potential of WHR in stabilizing renewable energy generation and improving overall energy utilization. However, to fully realize these benefits, ongoing research must focus on improving the efficiency and scalability of WHR systems, optimizing material properties, and exploring innovative designs. By continuing to refine and expand WHR technologies, industries can play a pivotal role in addressing global energy challenges, reducing their environmental footprint, and moving toward a more sustainable future.

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