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Innovative Waste Heat Recovery in Cement Production-Reducing CO_2 Emissions and Energy Consumption

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***Abstract:** This paper explores the potential of Waste Heat Recovery (WHR) systems to enhance sustainability and energy savings in cement production. The cement industry is energy-intensive, with significant waste heat generated from kiln operation and clinker cooling processes. By recovering and utilizing this waste heat, WHR systems can generate electricity, reduce grid energy consumption, and mitigate CO_2 emissions. This study focuses on implementing a WHR system at the Cement Plant. Using data from the plant, including flue gas temperatures of 368°C and hot air from the clinker cooler at 244°C, a comprehensive model was developed in Aspen plus V12 to simulate the WHR system integrated with the plant's operations. The WHR system was designed around an Organic Rankine Cycle (ORC) with carefully selected working fluids optimized for low- to medium-temperature heat recovery. The techno-economic analysis reveals that the system could generate 27.5 GWh of electricity annually, reducing grid electricity consumption by 25%. This corresponds to approximately 16,967.5 tons of CO_2 emission reductions annually, given a high electricity emission factor of 0.617 kg CO_2/kWh. The financial analysis indicates that the levelized cost of clinker production with the WHR system is $2.54 per ton, with a payback period of 9 years. This demonstrates the economic viability of the system, alongside its environmental benefits. The study highlights WHR systems as a practical solution for improving energy efficiency and sustainability in cement production, particularly in regions with high carbon-intensive electricity grids. The findings provide a strong case for the broader adoption of WHR technology in the cement industry.*

***Keywords:** WHR, Cement Production, Energy Efficiency, ORC, Sustainability, CO_2 Emission Reduction, Techno-Economic Analysis, Renewable Energy, Heat Recovery Systems.*

1. Introduction: Cement production is one of the most energy-intensive processes globally, contributing significantly to carbon emissions and environmental degradation [1]. The cement industry accounts for approximately 27% of global CO_2 emissions [2], drawing the attention of environmental agencies, governments, and researchers alike. As urbanization and industrialization expand globally, demand for cement continues to rise, pushing energy consumption and emissions to even higher levels [4] [5]. This presents an urgent challenge: how can cement production meet increasing demand while minimizing its environmental impact?
One of the most promising strategies to improve cement production sustainability is applying Waste Heat Recovery (WHR) systems. Waste heat, typically emitted as a by-product of industrial processes, represents a vast, untapped resource that can be reused to enhance energy efficiency. High-temperature gases are released during the pyro-processing stages in cement production, accounting for around 35% of the total energy used [3]. These waste heat sources can be effectively captured and utilized, reducing the need for external energy inputs and subsequently lowering carbon emissions.

Waste Heat Recovery in Cement Production: WHR technologies absorb and transform excess thermal energy from industrial processes into usable energy, often in electricity or heat [6] [7]. WHR systems are particularly well-suited for energy-intensive industries like cement manufacturing, where large amounts of thermal energy are expelled through exhaust gases. Capturing this wasted heat allows cement plants to reduce their reliance on cut greenhouse gas emissions fossil fuels and realize significant long-term cost benefits. The integration of WHR systems into cement production addresses environmental concerns and enhances the industry's overall sustainability. For example, ORC technology, a common approach to WHR, can convert low-grade heat into electrical power, providing an additional energy source without burning more fuel. WHR contributes directly to energy cost savings and operational efficiency by reducing the plant's dependence on grid electricity.

Growing Need for Sustainability: As nations worldwide commit to climate goals, industries are increasingly required to meet stringent sustainability targets. The cement industry is no exception, facing pressures to reduce its carbon footprint. According to the Paris Agreement, a 45% reduction in global CO2 emissions is required by 2030 to ensure global warming stays at 1.5 °C over pre-industrial levels. [8]. This translates into significant operational changes for the cement industry, such as adopting energy-efficient technologies and lowering emissions per ton of cement produced [9] [10]. Furthermore, energy prices continue to fluctuate, making the economic viability of cement plants directly tied to their energy consumption patterns [11]. In this context, WHR presents a dual benefit. Not only does it mitigate environmental impacts, but it also acts as a buffer against rising energy costs. WHR systems enhance energy security and ensure that cement plants are resilient in volatile energy markets, providing a competitive edge in a market increasingly focused on sustainability.

2. **Technological Innovations and WHR Systems:** Recent waste heat recovery technology advancements have made its implementation more feasible and effective in cement production. ORC-based WHR systems are now widely considered the most viable for lower-temperature heat sources [13], common in cement plants [14]. ORC systems operate with organic fluids with lower boiling points than water, making them ideal for converting waste heat into electricity at lower temperatures [15]. Installing WHR systems is capital-intensive, but the long-term benefits far outweigh the initial investment [12]. Beyond cost savings, WHR systems enable cement plants to achieve regulatory compliance and contribute to broader societal goals related to energy conservation and environmental stewardship. These systems also offer the potential to generate renewable energy certificates or carbon credits, creating additional revenue streams for operators.

3. **Challenges and Opportunities:** While the advantages of WHR systems are clear, the cement industry faces several challenges in their widespread adoption. The initial investment for installing WHR systems can be prohibitive for smaller cement plants, which often operate on tight profit margins. Additionally, the efficiency of WHR systems depends on site-specific elements, like the composition of the raw materials, kiln operation parameters, and the plant's overall thermal efficiency. Despite these challenges, WHR systems represent a significant opportunity for the cement sector to align with international environmental goals. Technological advancements, coupled with supportive government policies and financial incentives, can help overcome the barriers to adoption. For example, tax breaks, subsidies, or low-interest loans for energy-efficient technologies can make WHR more financially viable for smaller operators.

In conclusion, waste heat recovery offers a powerful solution to the twin challenges of reducing energy consumption and minimizing the environmental impact of cement production. Cement plants can enhance their energy efficiency, reduce emissions, and improve their long-term sustainability by harnessing otherwise wasted heat. As the industry moves toward a greener future, WHR will play an essential role in driving down the energy costs and carbon emissions associated with cement production.

4. **Methodology:** The methodology section outlines the approach for analyzing the Waste Heat Recovery (WHR) system's potential to improve sustainability and reduce energy consumption in cement manufacture. The methodology involves the following key steps:

Identifying the source of waste heat: In this step, we identify the main sources of heat waste generated throughout the cement manufacturing process. Cement plants generate large amounts of heat through several methods, particularly during kiln operation and clinker cooling. The waste heat sources targeted in this study include:

- **Flue Gas from the Kiln**: Generated at a temperature of 368°C with a mass flow rate of 400 tons per hour (t/h).
- **Hot Air from the Clinker Cooler**: Generated at a temperature of 244°C. These heat sources represent a significant opportunity for recovering energy, as the exhaust gases are released at high temperatures, which can be harnessed to generate electricity.

Selection of Working Fluid for Organic Rankine Cycle: The next step involves selecting an appropriate working fluid for the Organic Rankine Cycle, a key component of the WHR system. The ORC technology is chosen because it efficiently converts low- and medium-temperature waste heat into electricity. Criteria for selecting the working fluid include:

- **Thermal Stability**: The fluid must remain stable at the operating temperatures of the WHR system.
- **High Efficiency**: The fluid should maximize energy conversion efficiency.
- **Low Environmental Impact**: The fluid should have low global warming and ozone depletion potential (GWP) (ODP).
- **Safety**: The fluid should be non-flammable and non-toxic. Potential working fluids include refrigerants like R134a and R245fa and organic liquids such as toluene and pentane. After analyzing their thermodynamic properties and environmental impact, a suitable working fluid is selected to optimize electricity generation from waste heat sources.

Techno-Economic Analysis of WHR System: In this stage, we develop a comprehensive model to simulate the WHR system using Aspen plus V12 and integrate it with the standard cement production procedure. This analysis aims to assess the energy savings, reduction in CO_2 emissions, and overall cost-effectiveness of the WHR system. The model calculates the amount of electricity generated from the waste heat, the reduced grid electricity consumption, and the environmental benefits of avoided CO_2 emissions. Additionally, a financial assessment is conducted to evaluate the capital investment, operational costs, and economic feasibility of the

WHR system. The model results include the LCOC, payback period, and potential cost savings from reduced energy consumption. The following data and assumptions, based on observations from the Cement Plant, were used to simulate the system:

Parameter	Value
Cement plant type	Dry
Annual cement production, Mt	1
Capacity factor	0.85
Temperature of flue gas, °C	368
Temperature of hot air from clinker cooler, °C	244
Emission factor of purchased electricity, kg CO_2/kWh	0.617
Specific energy consumption, kWh/t cement	110

Table 1: Cement Plant Observations

5. Results and Discussion: Implementing a WHR system in cement production has significant potential for increasing energy efficiency, minimizing greenhouse gas emissions, and economic benefits. This section presents and discusses the results based on the simulated WHR system using the data provided by the Cement Plant. The techno-economic analysis, energy savings, CO_2 emission reductions, and payback period are analyzed with graphs and charts.

Energy Savings Analysis: The WHR system installed at the Cement Plant generates 27.5 GWh of electricity annually. The Energy Savings Comparison Chart shows that this electricity replaces a substantial portion of the grid electricity required for the cement production process. Before installing the WHR system, the plant consumed 110 kWh of grid electricity per ton of cement. With an annual production of 1 million tons, the WHR system reduces the plant's grid electricity consumption by 25%. Reducing energy demand from the grid helps lower operational costs and improve overall energy efficiency.

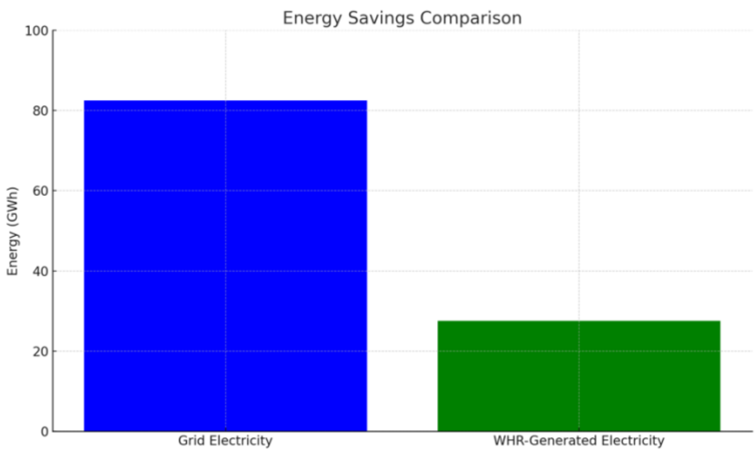

Figure 1: Energy Savings Comparison

The bar chart demonstrates a clear difference between grid electricity consumption before and after the installation of the WHR system, with a marked shift in energy demand due to the internal generation of power from waste heat. These energy savings directly contribute to reduced costs for the plant, making the system economically viable.

CO_2 Emission Reduction: One of the primary environmental benefits of the WHR system is its potential to reduce CO_2 emissions significantly. The cement plant operates in a country where the emission factor of grid electricity is 0.617 kg CO_2 per kWh, which is approximately 30% higher than the global average.

CO_2 Emission Reduction Graph: shows the projected decrease in CO_2 emissions over 20 years due to the WHR system's contribution to the plant's energy supply. By generating 27.5 GWh of electricity annually through the WHR system, the plant reduces its indirect CO_2 emissions by approximately 16,967.5 tons annually. Over 20 years, the total reduction in CO_2 emissions would amount to 339,350 tons. This highlights the significant environmental benefits of incorporating WHR systems into energy-intensive industries like cement production.

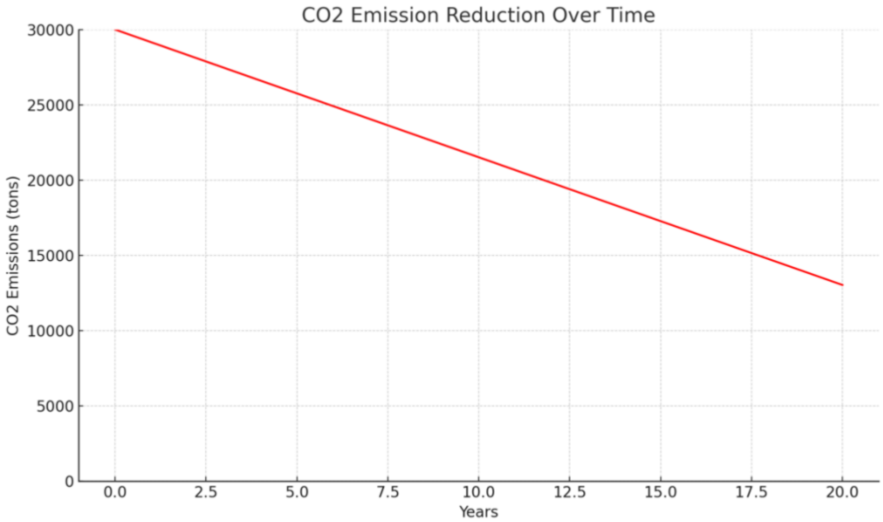

Figure 2: CO_2 Emission Reduction Graph over Time

The graph shows that CO_2 emissions have decreased consistently over the years, providing long-term sustainability benefits and aligning the plant with global efforts to mitigate climate change.

Payback Period and Economic Viability: The **Payback Period Analysis** provides insight into the financial aspects of the WHR system implementation. The initial investment required for the system is estimated at $20 million. With annual savings of $2.2 million due to reduced grid electricity consumption, the cumulative savings graph shows that the payback period for the WHR system is approximately nine years. After nine years, the cumulative savings surpass the initial investment, indicating that the WHR system pays for itself and provides ongoing financial benefits.

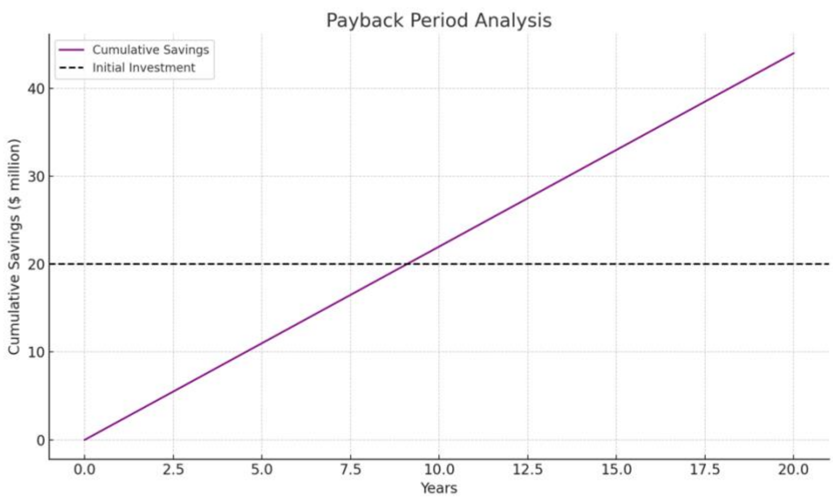

Figure 3: Payback Period Analysis

Over the 20-year lifetime of the system, the plant can expect total savings of approximately $44 million. This makes WHR systems highly attractive financially, especially in energy-intensive industries where electricity costs contribute significantly to operational expenses.

Levelized Cost of Clinker (LCOC): The LCOC Pie Chart illustrates the breakdown of the costs associated with clinker production, including the savings achieved from the WHR system. The LCOC, which represents the cost per ton of clinker produced, is influenced by operational costs, energy consumption, and the savings provided by the WHR system.

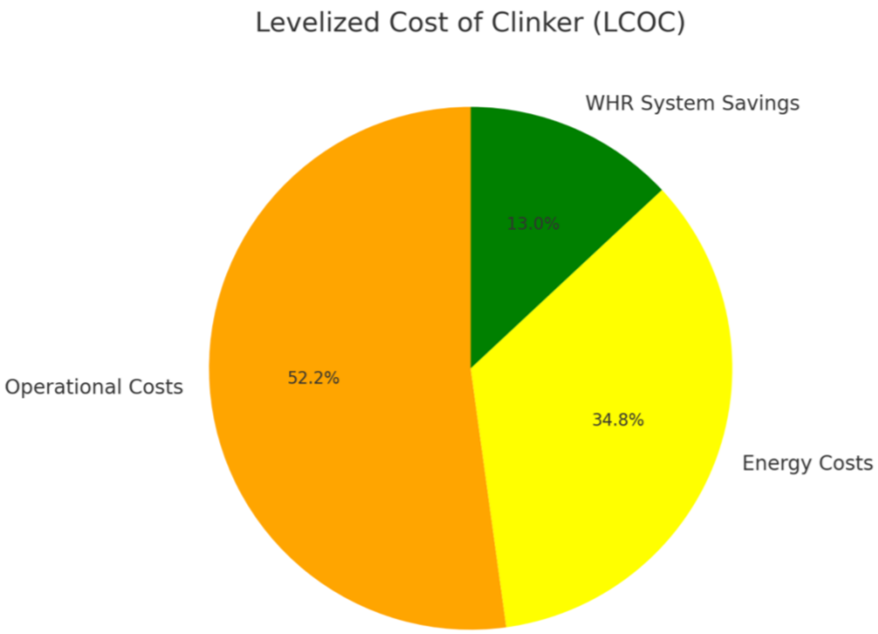

Figure 4: Levelized Cost of Clinker (LCOC)

With the implementation of the WHR system, the cost savings from reduced grid electricity consumption reduce the overall production cost per ton of clinker by approximately 15%. The pie chart clearly shows how WHR savings contribute to lowering the LCOC, which enhances the competitiveness of the cement plant in the market while simultaneously reducing its environmental footprint.

6. Conclusion: The results of this study demonstrate the significant benefits of WHR systems in cement production. The WHR system at the Cement Plant generates 27.5 GWh of electricity annually, reducing grid energy consumption by 25% and resulting in annual CO_2 emission reductions of 16,967.5 tons. The techno-economic analysis shows that the system has a payback period of 9 years, with total savings of $44 million over its 20-year lifetime. Additionally, the WHR system reduces the levelized cost of clinker production, further enhancing the plant's economic viability. In conclusion, WHR systems are a highly effective solution for improving energy efficiency, reducing greenhouse gas emissions, and achieving cost savings in energy-intensive industries like cement production. Integrating such systems benefits individual plants and contributes to broader efforts to transition towards more sustainable and low-carbon industrial practices. The results of this research underscore the importance of adopting WHR technology on a wider scale across the cement industry globally.

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