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Enhancing Sustainability and Energy Savings in Cement Production via Waste Heat Recovery †

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Abstract: Cement production is one of the most energy-intensive industries. During the clinker formation and cooling processes, excess heat is lost to the atmosphere. For this reason, using waste heat to generate useful energy is considered the most promising approach to sustainable cement production. Many cement plants still face challenges in energy efficiency due to historically low energy prices and subsidies in Uzbekistan, which have deterred the adoption of waste heat recovery (WHR) technologies. This study conducts a techno-economic analysis of WHR technologies for a cement plant with an annual capacity of 1 million metric tons (Mt). It evaluates potential energy savings and economic benefits, identifying key waste heat sources, such as preheater flue gas and clinker cooling air, with a total recoverable waste heat of 60.52 MW. The implementation of WHR systems can significantly enhance energy efficiency and reduce operational costs. Results show that WHR can reduce clinker production costs by 3.81% and the levelized cost of clinkers by 7.49%, while cutting annual indirect CO_2 emissions by 63.26%. Given the legislative support and recent energy price liberalization, the first WHR projects are expected to start in 2025 in Uzbekistan. This analysis offers valuable insights for adopting WHR technologies to improve sustainability and competitiveness in Uzbekistan's cement industry.

Keywords: waste heat recovery; cement production; energy efficiency; environmental improvements; sustainability; cost reduction

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1. Introduction

The cement industry is one of the most energy-intensive industries worldwide, while at the same time, it has a very high impact on the environment [1]. The rapidly increasing demand for cement, driven by urbanization and industrialization, poses considerable challenges for the industry regarding meeting production needs and minimizing its environmental impact. The urgency for the formulation of innovative strategies that not only enhance energy efficiency but also reduce greenhouse gas emissions is seen in the background.

Cement is manufactured through many processing steps, but the most energy-intensive step is clinker formation [2]. Clinkers are formed by heating a mixture of mainly limestone and other additives—milled, in proper proportion—into fine powder in a kiln. It is a highly exothermic process in which a large proportion of the released heat is lost to the atmosphere during clinker formation and subsequent cooling. Energy consumption represents 50–60%

of the total manufacturing cost, with thermal energy alone accounting for 20–25% [3]. On average, specific energy consumption is 3.4 GJ per ton for dry cement production and 6.7 GJ per ton for wet cement production, while the best available technology can reduce this to 2.92 GJ per ton.

Regarding Uzbekistan's cement industry, the current primary focus of decarbonization efforts is the implementation of energy saving technologies. Since 2015, the number of cement plants in Uzbekistan has increased seven times, and the total production capacity has more than doubled. The average energy consumption has decreased two-fold, primarily due to the construction of new dry cement plants. However, many cement plants still face significant challenges in energy saving [4]. The reason for this is that, until now, fuel and electricity prices were not liberalized and were based on energy subsidies [5]. Consequently, the extremely low operating costs eliminated the incentive to develop energy-saving and waste heat recovery (WHR) measures. Since the cost of energy from waste heat is higher than that from the grid, none of the cement plants have implemented WHR technologies. The rapid growth of the business sector and the population has led to fuel energy shortages in the recent two years, prompting the industrial sectors to adopt energy-efficient measures [6,7]. Therefore, cement plants are expected to start installing WHR units from 2025.

Waste heat in the cement industry is typically of medium type (100–400 °C), mainly found in preheater flue gas and clinker cooling air [8]. WHR involves several technologies such as raw material drying and electricity generation using a power cycle (organic Rankine cycle (ORC), Kalina cycle) designed to capture and reuse the heat generated during cement production. The effectiveness of these technologies can be assessed through techno-economic analysis in specific cases, taking into account the economic situation of the cement company and the cost of fuel and raw materials [9].

In this work, a comprehensive techno-economic analysis of WHR technologies is carried out for a cement plant with an annual production capacity of 1 million metric tons (Mt). The analysis aims to evaluate the potential energy savings and economic benefits of implementing WHR technologies. By examining the technical feasibility and economic viability, this study provides insights into how this technology can enhance energy efficiency and reduce operational costs within the cement manufacturing process. This study involves identifying key waste heat sources, selecting appropriate working fluids for the ORC system, modeling the WHR system using Aspen Plus, and conducting a techno-economic analysis to evaluate energy savings, economic benefits, and environmental impacts. The findings are intended to guide decision making for the adoption of WHR solutions in the industry, considering the specific production conditions and economic factors relevant to the cement plant in question.

2. Methodology

The methodology comprises several key steps, including the identification of waste heat sources, the selection of working fluids in the WHR, and the modeling and cost analysis of heat recovery systems. Each key step is described in the subsections below.

2.1. Waste Heat Source Identification

The first step in the methodology involves identifying and quantifying the primary sources of waste heat within the cement production process. The focus is on the clinker formation and cooling stages, which are known to be the most energy-intensive phases. Two significant sources of waste heat are identified: (1) preheater flue gas—the hot gases exiting the preheater tower, primarily used for preheating raw materials before they enter the kiln; (2) cooler gas stream—the hot air exiting the clinker cooler, which cools the clinker coming out of the kiln.

Figure 1 illustrates the integration of a WHR unit with the cement production process, focusing on the preheater flue gas and hot air from the clinker cooling system. The preheater flue gas and hot air are directed into the WHR unit, where their thermal energy is utilized to generate electrical power through a turbine and generator system, enhancing the overall energy efficiency.

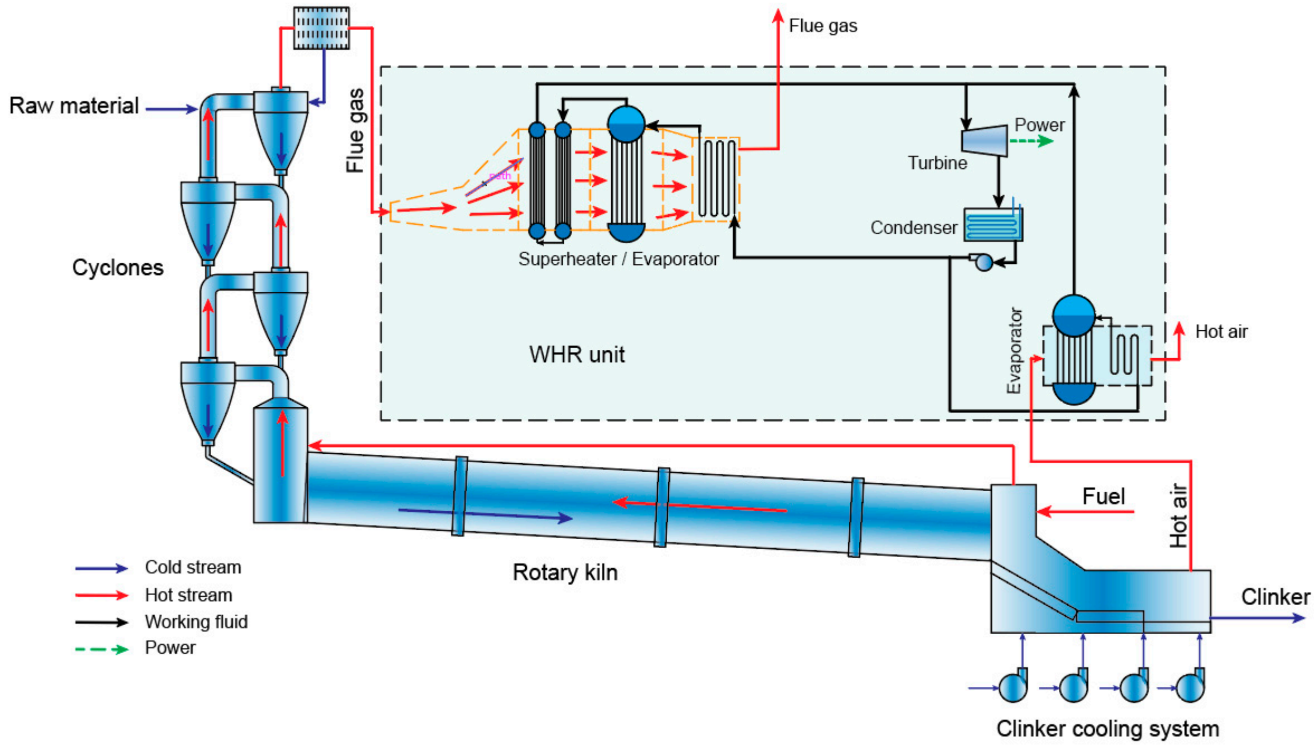

Figure 1. Schematic of a WHR system in cement production (source: own elaboration).

2.2. Selection of Working Fluid for ORC

The methodology for selecting an appropriate working fluid for the ORC system in a cement plant's waste heat recovery involves a systematic evaluation of thermodynamic properties, environmental and safety considerations, and economic factors. Given the high-temperature flue gas and hot air from clinker cooling as the waste heat sources, it is essential to follow a structured approach to identify the most suitable working fluid. First, we analyze the thermodynamic properties of potential working fluids. These properties are crucial in determining the efficiency and power output of the ORC system. The working fluid must have a boiling point that aligns with the temperature of the waste heat sources to ensure effective heat absorption. Next, we consider the environmental impact and safety profile of each working fluid. These factors are critical for sustainable and safe operation. Fluids with a lower global warming potential (GWP) are preferred to minimize the environmental impact. The economic feasibility of the working fluid is assessed by considering its cost, availability, and compatibility with ORC system materials. The working fluid should be readily available and cost-effective. Different working fluids offer varying efficiencies at different temperature ranges. We evaluate the performance of fluids like R245fa, R134a, and Toluene based on their efficiency in the given temperature range. Table 1 lists the properties of the working fluids selected for this work.

Table 1. Properties of the selected working fluids [10,11].

Working Fluid	Boiling Point, °C	Critical Temperature, °C
R245fa	15.04	153.86
R134a	−26.07	101.06
Toluene	110.6	318.6

2.3. Techno-Economic Analysis of WHR System

The third step involves model development using Aspen Plus V12 to simulate the WHR system and integrate it with the baseline cement production model. In order to build a model, we first need to define the initial data comprehensively. These initial data set the foundation for the modeling process and include critical parameters such as the type of cement plant (dry process), the capacity factor (0.85), the temperature and mass flow of the flue gas (368 °C, 400 t/h), and the temperature of the hot air from the clinker cooler (244 °C) (see Table 2). These data were obtained as a result of observations from Jizzakh cement plant, one of the cement plants in Uzbekistan.

Table 2. Initial data and assumptions.

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

The primary objective of WHR systems is to reduce grid electricity consumption by generating electricity from waste heat. Currently, the emission factor of electricity in Uzbekistan's power grid is 0.617 kg CO_2 per kWh [12], which is 30% higher than the global average. This indicates a heavy reliance on fossil fuels for power generation. Consequently, it is crucial to calculate the sum of annual indirect CO_2 emissions (*AIE*) to understand the environmental impact and potential benefits of implementing WHR systems. It is calculated using Equation (1) (modified from ref. [13]).

$$AIE = \frac{AC_{cement} \cdot SEC \cdot EF}{1000} \tag{1}$$

where AC_{cement}—annual cement production, t; *SEC*—specific energy consumption, kWh/t_{cement}; *EF*—emission factor of electricity, kg CO_2/kWh.

The levelized cost of clinker (LCOC) and cost of produced clinker depend on parameters such as annual capital and operating costs, plant lifetime, and capacity factor. These parameters are derived from our previous work.

3. Results and Discussion

The analysis identifies significant sources of recoverable waste heat within the cement production process, specifically from the preheater flue gas and the cooler gas stream. The total recoverable waste heat amounts to 60.52 MW, with 29.7 MW from the preheater flue gas and 30.82 MW from the cooler gas stream. As for the impact of ORC working fluids, R245fa provides a balanced performance with a net power output of 12.927 MW, combining moderate efficiency. R134a, while effective in some contexts, produces a lower power output of 11.505 MW (11.02% less than R245fa), making it less suitable for higher-temperature waste heat recovery (see Figure 2). Toluene, with a power output of 14.866 MW (15.00% more than R245fa), offers the highest efficiency. The calculated thermal efficiencies for the ORC with different working fluids are as follows: R245fa—21.36%, R134a—19.01%, and Toluene—24.56%. These efficiencies are compared with those reported in previous studies, where the thermal efficiencies were 23% for R245fa [14], 14% for R134a [15], and 21% for Toluene [16] (see Table 3).

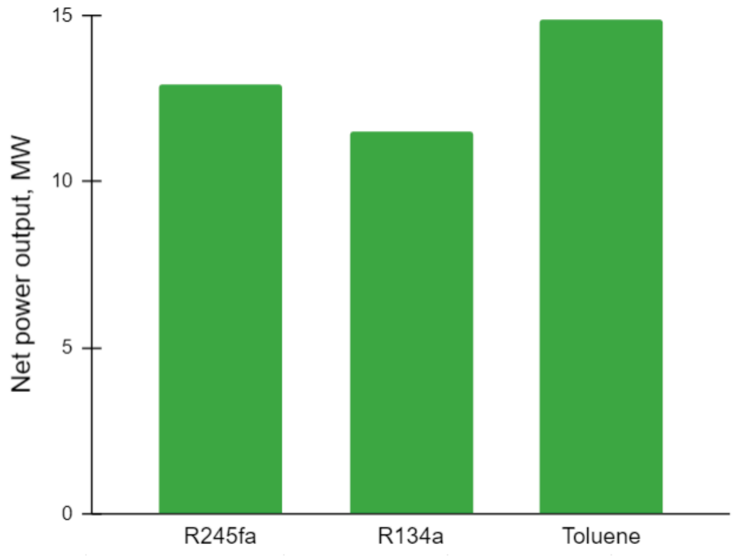

Figure 2. Net power output values of the WHR using different working fluids.

Table 3. Thermal efficiency of selected working fluids.

Working Fluid	Thermal Efficiency (%)		Reference
	This Study	Relevant Work	
R245fa	21.36	23	[14]
R134a	19.01	14	[15]
Toluene	24.56	21	[16]

If we consider safety and environmental characteristics, R245fa's performance is attributed to its favorable latent heat of vaporization and specific heat capacity, which enable efficient heat absorption and conversion. Additionally, R245fa is non-toxic and non-flammable, making it a reliable option for WHR systems in industrial settings. Its moderate GWP also adds to its appeal from an environmental standpoint. R134a's thermodynamic properties result in less effective heat absorption and conversion at the temperatures encountered in the preheater flue gas and clinker cooler streams. However, R134a is non-toxic and non-flammable, which makes it safe for use in various industrial applications. Despite these advantages, its higher GWP compared to R245fa makes it less favorable from an environmental perspective. Toluene's high latent heat of vaporization and specific heat capacity enable it to maximize energy recovery from the preheater flue gas and cooler gas streams. However, Toluene's flammability and toxicity pose significant safety concerns, requiring stringent handling measures and safety protocols. Based on the brief evaluation, R245fa emerges as the most balanced choice for the cement plant's waste heat recovery ORC system.

The implementation of WHR systems in cement plants has shown significant economic and environmental benefits. The cost analysis reveals that the introduction of WHR systems reduces the cost of clinker production. For a standard cement plant, the cost of producing clinker is USD 58.20 per ton. However, when a WHR system is integrated, the cost decreases to USD 55.98 per ton, representing a cost reduction of 3.81%. Moreover, the analysis shows that the LCOC decreases from USD 45.95 per ton in a standard cement plant to USD 42.50 per ton with the implementation of WHR technology, indicating a 7.49% reduction. This reduction in cost can be attributed to the energy savings achieved through the WHR system, which captures and utilizes waste heat for power generation, thereby reducing the need for external energy sources.

The selected cement plant in this study emits a total of about 0.9 Mt of CO_2 (about 91% directly and the rest indirectly). The environmental benefits of WHR systems are equally compelling. A primary measure of environmental impact is the reduction in annual indirect CO_2 emissions associated with clinker production. For a standard cement plant without WHR, the annual indirect emissions amount to 81.44 kt of CO_2. In contrast, a plant equipped with WHR systems produces only 29.9 kt of CO_2 annually. This substantial reduction, representing a 63.26% decrease, is a direct result of decreased reliance on fossil fuels and the improved energy efficiency provided by the WHR system.

4. Conclusions

The integration of WHR systems in cement production processes demonstrates substantial economic and environmental benefits, making it a compelling strategy for enhancing the sustainability and efficiency of the industry. This work has comprehensively analyzed the techno-economic and environmental impacts of implementing WHR systems, focusing on their influence on clinker production costs, indirect CO_2 emissions, power output, and overall plant performance in a 1 Mt/year capacity cement plant.

The overall key findings are presented below:

- Until recent years, potential energy-efficient technologies have not been used in cement plants in Uzbekistan due to low fuel and electricity prices.
- From 2025 onwards, cement plants in Uzbekistan are expected to start installing WHR units as energy prices become more liberalized and the economic benefits of energy efficiency become more apparent.
- The total power generated from all waste heat sources amounts to 12.927 MW when using R245fa, with 5.026 MW produced from the preheater flue gas and 7.901 MW from the cooler gas stream.
- The findings reveal that WHR systems can reduce the cost of clinker production. The cost per ton of a clinker can decrease from USD 58.20 to USD 55.98, representing a cost reduction potential of 3.81%. Additionally, the LCOC can be reduced from USD 45.95 to USD 42.50 per ton, indicating a 7.49% reduction.
- Environmentally, the implementation of WHR systems leads to a substantial decrease in a plant's indirect CO_2 emissions. Annual indirect emissions can be reduced by 63.26%, from 81.44 kt of CO_2 to 29.9 kt.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

WHR	Waste heat recovery
ORC	Organic Rankine cycle
GWP	Global warming potential
AIE	Annual indirect CO_2 emissions
LCOC	Levelized cost of clinker

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