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# Thermodynamic analysis of a waste heat recovery power generation system in a cement plant in southern Perú

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## ABSTRACT

For developing nations like South America to achieve an energy transition, industrial plants must optimize their energy performance. The installation of a waste heat recovery system at a cement plant in southern Peru was examined. The organic Rankine cycle (ORC) was chosen using the VDI 2225 methodology. Toluene, decane, D5 (decamethylcyclopentasiloxane), and MD4M (tetradecamethylhexasiloxane) were the four working fluids taken into consideration for the analysis. The findings show that all fluids' net specific power and cycle efficiency greatly increase with exhaust gas temperature, with toluene and decane performing the best. While higher condensation temperatures had a negative impact on efficiency, pre-turbine superheating proved to have a negligible effect on the parameters studied. Unlike hydrocarbon-based fluids, D5 and MD4M siloxanes present promising potential for future ORC applications due to their greater thermal stability, lower toxicity, and reduced environmental impact. A complementary $CO_2$ capture and utilization system is also suggested to produce urea from kiln off gases, providing a sustainable and integrated approach to fertilizer production and energy recovery. This work offers a window into the Peruvian cement industry's use of ORC-based carbon utilization and waste heat recovery technologies.

**Keywords:** cement plant, energy transition, organic Rankine cycle, VDI 2225, waste heat recovery.

## INTRODUCTION

In South America, there are challenges to the energy transition in industry, one of which is increasing the efficiency of production processes. This increase stems from the intention to use existing resources sustainably with a vision for the future [1, 2]. Specifically, in Peru, the development of more efficient industrial processes is not a fundamental pillar of the country's energy transition; however, the use of renewable energies has gained significant importance [3]. Currently, there are several untapped sources of waste heat, mainly from high-temperature industrial processes, such as those in the food, paper, metallurgical, chemical, cement, and ceramic industries. Harnessing this heat can be very useful for heating other processes, producing steam, or for heating [4, 5].

One of the sources of waste heat with a significant impact on greenhouse gas emissions is the cement industry. Recent estimates indicate that this industry's contribution to global $CO_2$ emissions ranges from 5% to 10%, with fossil fuel consumption and direct emissions from the clinker production process accounting for over half of these emissions [6, 7]. Furthermore, the energy efficiency of this process, due to the underutilization of waste heat, is typically lower compared to other energy-intensive industrial processes [8]. Therefore, there are challenges regarding energy and emissions management in the cement industry.

Specifically in Peru, cement production has remained stable in recent years. Within national production, two cement plants, which in 2017 were among the top 100 cement producers worldwide, account for approximately 80% of total production [9]. While several cement plants in the country have committed to energy efficiency and emissions reduction goals, there are currently no waste heat recovery projects in cement plant kilns. Currently, cement plants in Peru use natural gas and coal in their kilns, both facing a challenge in the utilization of waste heat [9].

In Peruvian industry, several local limitations influence the feasibility of implementing waste heat recovery technologies. First, electricity rates for large industries in Peru are typically high compared to the market, making on-site power generation more economically attractive for these industries. Second, despite abundant water resources in areas like Arequipa, the location of these plants in southern Peru often faces a shortage of cooling water and high ambient temperatures, limiting the applicability of water-dependent technologies such as Rankine steam cycles [10]. Finally, Peru currently has limited access to industrial green credit, hindering large industries' entry into the carbon market [11].

In developing countries like Peru, waste heat recovery in the cement industry presents an opportunity for electricity generation. The process gas streams have sufficiently high temperatures and flow rates to drive thermodynamic cycles such as the Rankine cycle. Its implementation would increase the plant's energy efficiency and, depending on the region, reduce fossil fuel consumption [12, 13]. Technical and economic studies demonstrate that waste heat recovery technology can produce tens to hundreds of kW per ton of clinker in cement plants. Furthermore, it contributes to the industry's carbon offsetting efforts, in addition to providing a second alternative source of electricity for the plant, and in some cases, for a city [14, 15].

It is important to note that some Peruvian cement plants operate at altitudes above 2000 meters above sea level, so the lower air density at that altitude affects the performance of their cooling systems. This makes it harder to use processes that need high-pressure steam, like Rankine or Kalina cycles [16]. In recent years, though, organic Rankine cycles have become more popular. They can work at higher condensation temperatures, which makes them better for high-altitude uses, as long as they are carefully designed first. Also, the properties of process kiln exhaust gases, like those in any other industry, change depending on things like the quality of the fuel and the amount of work being done. This variability makes it even more important to choose working fluids that can keep their performance stable even when the heat input is not steady [17].

Recent case studies and reviews indicate that organic Rankine cycles (ORCs) and conventional steam cycles are viable alternatives for medium-low temperature sources, frequently found in kilns and clinker coolers within plants situated in developing nations. Wang et al. [15] assessed the amalgamation of ORC cycles employing hot air from the kiln cooler (220 °C) and five operational fluids. The ORCs generated between 67.9 and 81.2 GWh/year, saving up to 2436 t of coal and reducing between 7743 and 9268 t of $CO_2$, in addition to decreasing $SO_2$, $NO_x$, and other environmental impacts. Finally, the economic analysis showed payback periods of 2.74 to 3.42 years, with R601 being the best-performing fluid. Rad and Mohammadi [18] analyzed the use of waste heat from the chimneys of the Sabzevar cement plant to generate power through a steam cycle, seeking to improve energy efficiency. They first found that increasing the boiler pressure reduced the total energy recovery but improved the cycle efficiency. Then, the optimum pressure to maximize exergy absorption was 891.8 kPa, while the maximum net power, considering the fan consumption, was reached at 1398 kPa, where the highest energy and exergy efficiencies were also obtained. Junior et al. [19] evaluated the Kalina cycle to generate electricity from the waste heat of the cyclonic preheater in a Brazilian cement plant that produces 2,100 tons of clinker per day. EES models were used, and the cycle was optimized for net power, efficiency, and costs. It was found that adjusting the concentration and pressures of ammonia improves performance and reduces costs. Finally, a generation of 2429 kW was achieved with thermal efficiencies of 23.3% and exergetic efficiencies of 47.8%, with costs competitive in the Brazilian market.

Similar studies, but with an additional focus on greater sustainability, have been developed. For example, Ahmed et al. [20] studied the implementation of an organic Rankine cycle using organic fluids instead of water to convert low- and medium-temperature (80–300 °C) thermal energy into electricity. They first presented the design of an ORC based on real data from a cement plant, where the choice of fluid, in this case R134a, was key. Combined with a gas turbine, the system can generate around 1 MW of power. Ustaoglu et al. [21] evaluated the thermodynamic process in a rotary kiln at a cement plant. The analyses showed that 30.5 MW of waste heat is expelled in the exhaust gases, so an organic Rankine cycle with different working fluids was applied. The refrigerant R245fa offered the best performance at 13%, surpassing R600a at 9.8%. It is concluded that the isentropic fluids R245fa and R142b are suitable for high pressures and low condensation temperatures, while R600 and R600a have limitations. Ishaq et al. [22] examined a system that uses waste heat recovered from cement slag to power a Rankine reheat cycle, hydrogen compression, and a copper-chlorine thermochemical cycle. The system enables the production of clean hydrogen by utilizing industrial heat, thus reducing operating costs and improving energy use. Modeled in Aspen Plus, the system achieved an overall energy efficiency of 32.5%. Therefore, various technologies can be implemented in cement plants to improve the energy efficiency of these processes.

In recent years, researchers have increasingly focused on improving organic Rankine cycle systems for industrial waste heat recovery. Much of this work has centered on practical issues, such as using aromatic working fluids at higher operating temperatures, more realistic modeling of expander performance, and system-level optimization rather than component-level optimization. Studies published between 2022 and 2024 also show a growing interest in reclaimed ORC designs and the use of data-driven tools, including machine learning methods, to facilitate parameter selection and performance improvement [17, 23–26]. Recent studies in developing countries, in particular, are aimed at transitioning to ORC designs better suited for medium- and high-grade waste heat in industrial applications.

To date, researchers have begun to look beyond power generation and explore how ORC systems could be combined with carbon capture and utilization options, as is being done in the petroleum industry, for example. In several recent studies, low-pressure $CO_2$ streams from industrial processes are not treated as waste but are instead redirected to downstream synthesis routes, including the production of urea and methanol [27, 28]. Because urea is often an agro-industrial necessity in developing countries, its integration with a carbon dioxide capture system is promising and could help alleviate some long-term costs [29, 30]. Rather than considering carbon dioxide recovery as an isolated process, these studies emphasize its role within a broader industrial system. Therefore, carbon dioxide-derived urea as an added benefit when evaluating waste heat recovery systems may hold potential in developing countries.

Cement production is a major contributor to $CO_2$ emissions, and current Peruvian plants underutilize available waste heat. Operational constraints, such as high-altitude conditions, limited cooling water, and high electricity costs, further limit the feasibility of conventional heat recovery technologies. This highlights the need for a practical evaluation of waste heat recovery systems adapted to Peruvian conditions. Although waste heat recovery has advanced globally, no study has assessed its application in Peruvian cement plants, where local electricity costs, high altitude operation, and a lack of cooling water present particular technical and financial difficulties. Therefore, this study aims to evaluate the implementation of this system through a thermodynamic cycle, considering the kiln of a cement plant in southern Peru as a case study. To this end, the cement plant in question is first described, then the most appropriate energy generation technology is selected based on technical and economic aspects, and then the heat recovery system and its thermodynamic modeling are described. In addition to the implementation of this heat recovery system, a $CO_2$ capture system is proposed to generate a subprocess for the production of urea, a highly consumed fertilizer in the agricultural sector in Latin America.

This work takes a slightly different route from most earlier studies. Instead of selecting an ORC configuration based only on thermodynamic performance, the analysis starts by using a VDI 2225–based procedure and then compares several working fluids under the same operating conditions for a cement plant in Peru. Additionally, the system is not regarded as a stand-alone power unit. It is examined in conjunction with a $CO_2$ capture stage and a urea synthesis procedure, so the recovered heat is connected to both the generation of electricity and the subsequent utilization of captured carbon. The study can move away from idealized ORC cases and toward a more practical industrial application.

## METHODOLOGY

### Kiln description

The operational context of the cement kiln is described in this subsection, along with the features of the heat source that is used to recover waste heat. This study uses a cement plant in southern Peru as a case study. The average daytime temperature is 20°, and the climate is dry. The plant currently uses a dry process to make cement at a height of about 2.500 meters above sea level. The plant produces clinker by burning calcareous aggregate in a sizable horizontal rotary kiln. Its daily capacity is 5.000 tons. Every day, about 96 tons of pulverized coal are used, and the process temperature ranges from 1.400 to 1.500 °C. Bituminous coal, imported from Colombia, is utilized.

## Thermodynamic cycle selection (VDI 2225)

The steps used to determine the best thermodynamic cycle based on the kiln's operating characteristics are described below using the VDI 2225 design methodology. Instead of depending on a single performance criterion, this method enables the consideration of various technical, economic, and operational factors pertinent to Peruvian cement plants.

To determine the suitable power generation system for the case study, the VDI 2225 methodology will assess the technical and economic criteria of existing technologies suggested in various global regions. The following thermodynamic cycles are taken into account for this evaluation: the steam Rankine cycle (SRC), the organic Rankine cycle, the Kalina cycle (KAC), and the Brayton cycle (BRC). It is clear that each technology has its own set of features and ways of working. It would be helpful to compare a few systems to see which parameters work best, but this doesn't mean that one technology is better than the others. The performance of these systems is also greatly affected by how they work, the environment they work in, and other things that affect their analysis. But the next review will be done in a general way.

VDI 2225 states that a score of 0 represents non-compliance, 1 is minimally adequate, 2 is acceptable, 3 is good, and 4 is ideal for each criterion. This facilitates the identification of the best and worst types of propulsion. While the letter "p" denotes the score, the letter "g" denotes the weighting of each criterion, signifying the significance of technical and economic factors for propulsion. By dividing the variant's total score by its ideal score, the degree of appreciation is determined.

### *Technical evaluation*

Since it establishes the percentage of recovered thermal energy that is actually converted into usable electricity, the energy efficiency of the cycle (T1) is a crucial factor in the selection of waste heat power generation systems in cement plants. An improved cycle uses kiln and clinker cooler gases more effectively, lessens reliance on fossil fuels, and lowers $CO_2$ emissions per ton of clinker produced [12]. Furthermore, energy efficiency is closely linked to economic viability, since more efficient cycles generate more electricity with the same investment, improving financial return indicators and competitiveness against the cost of the electricity grid in developing countries [13, 14].

The operating temperature range and adaptability to the available waste heat (T2) are essential aspects when evaluating thermodynamic cycles in a cement plant, since kiln and clinker cooler gases present different thermal levels ranging from very high temperatures (800–1000 °C) to medium and low ranges (200–400 °C). A cycle that does not adapt to the available thermal profile loses much of its recovery potential, reducing the overall system efficiency and project profitability. Technologies such as the steam Rankine cycle require high temperatures, while the organic Rankine cycle or Kalina cycle show better performance in the medium and low ranges, making them more versatile in real-life industrial settings in developing countries [13, 15]. Thus, the correct correspondence between the waste stream temperatures and the selected technology maximizes energy recovery and minimizes exergy losses [14].

Technological maturity and operational reliability (T3) are typically more significant than minor improvements in theoretical performance when choosing a thermodynamic cycle for waste heat recovery in a cement plant. Technologies like the organic Rankine cycle and the steam Rankine cycle have been used in cement plants and other harsh industrial settings for many years, and their behavior during continuous operation is well known. Because of its lengthy operating history, there is less technical uncertainty during design and startup, and once the system is in use, there is less chance of unplanned shutdowns [12]. On the other hand, alternatives like the Kalina or Brayton cycles are still uncommon in the cement industry, despite being appealing from an energy perspective in specific temperature ranges. Because there are fewer actual installations, it is more difficult to forecast maintenance needs and long-term availability, which can have a detrimental impact on plant operations and expenses [15]. Therefore, selecting a proven technology increases the likelihood that the anticipated energy savings will be realized in regular operation, enhancing the project's overall viability [14].

How the waste heat recovery system integrates with the cement plant as it currently runs is another crucial issue (T4). Kiln and clinker cooler conditions are not constant during daily operations; different fuels are used, production rates fluctuate, and operating strategies are modified based on plant requirements. The quantity of recoverable waste heat is therefore continuously fluctuating. Because it can continue to recover heat without interfering with the primary production process, a system that can adapt to these changes is therefore far more practical [31]. Modular and scalable system designs are also simpler to implement from an installation perspective, particularly in plants with limited space where new equipment needs to be added to pre-existing layouts. This lessens the effort needed for installation and operation and facilitates the recovery system's integration with existing infrastructure, including emissions control units [32]. Overall, this type of flexibility increases the likelihood that the project will produce a steady and dependable return over the plant's operating life and helps prevent needless downtime [32].

### *Economic evaluation*

One of the primary determinants of whether a project proceeds in a cement plant is frequently the initial cost of a waste heat recovery system (E1). Although technologies like steam Rankine cycles are well-established, their complicated equipment and requirement to operate at high pressures typically result in higher installation costs. On the other hand, even though their efficiency might be a little lower, systems like the organic Rankine cycle are typically simpler to install because they come in modular designs and require less extensive integration. These upfront expenses are particularly crucial in many developing-country contexts due to financial constraints. Because of this, choices are usually made based on whether the anticipated energy savings and possible decrease in carbon emissions over the system's operating life can justify the initial investment [31–33].

When assessing waste heat recovery power generation systems in cement plants, operation and maintenance costs (E2) are crucial because they have a direct impact on long-term profitability as well as the levelized cost of energy produced. Even when the initial investment (CAPEX) is high, technologies with lower maintenance requirements, like the organic Rankine cycle, may be more appealing than more complicated options with higher operational demands, like the steam Rankine cycle or supercritical Brayton cycles. Furthermore, the frequency of component replacement, the availability of spare parts, and the need for specialized personnel for operation and maintenance all affect the system's dependability and anticipated service life. As a result, OPEX plays a crucial role in guaranteeing the economic viability and sustainability of contemporary technologies in developing nations [31, 33, 34].

Because they show the payback period and the cost per kWh produced, the return on investment and the levelized cost of energy (E3) are essential for assessing the economic feasibility of waste heat recovery systems in cement plants. According to studies, ORC cycles in cement plants are very competitive, with payback periods ranging from 2.7 to 3.4 years [13]. In other instances, specific electricity generation costs and internal rates of return are competitive when taking into account local electricity rates and incentives, according to an analysis of simple and regenerative ORCs in cement plants [31]. Additionally, levelized energy cost analyses for various cycles (ORC, Kalina, and trilateral cycles) in cement plants in Latin America demonstrate how various configurations can provide levelized energy costs that either match or surpass grid costs, making them financially appealing [14].

A cement plant's ability to proceed with a waste heat recovery project is primarily determined by economic risk and financing conditions (E4), which have a direct impact on the speed at which the investment can be recouped and the final cost of the electricity produced. Without sufficient financing mechanisms, technically sound projects can become unviable due to fluctuations in interest rates, country risk, or electricity prices [14]. While technical and economic evaluations in some countries demonstrate that differences in the cost of capital have a substantial impact on financial indicators, recent studies emphasize that the deployment of these technologies is limited in Latin America by the absence of competitive financial systems [35]. Furthermore, exergoeconomic evaluations verify that both technological design and advantageous financing conditions are necessary for profitability [36].

Table 1 and Table 2 show the parameters considered as technical and economic evaluation criteria, respectively. Figure 1 shows these parameters evaluated according to VDI 2225, and their respective comparison considering the ideal weighting case. The Organic Rankine Cycle technology outperformed steam Rankine, Kalina, and Brayton alternatives in the systematic evaluation carried out using the VDI 2225 methodology, obtaining the highest score in both the technical and economic categories. Its high adaptability to the range of residual temperatures presents in kilns and clinker coolers, its flexibility for integration into cement plants, and its technological maturity, widely demonstrated in the industry, are the main reasons for this success. Compared to other less popular technologies, ORC reduces financial risk by offering competitive OPEX, moderate CAPEX, and an attractive LCOE. All these findings support the selection of ORC as the most practical and comprehensive option for a power generation system with waste heat recovery in a cement plant in southern Peru.

## Heat recovery and system modelling

After selecting the appropriate cycle, this subsection describes the configuration of the proposed heat recovery system and the modeling framework used to evaluate its performance. Particular emphasis is placed on the evaporator, condenser, and heat exchangers connecting the ORC to the kiln exhaust flow.

To evaluate the behavior of the heat recovery system, we will first define some operating parameters of the Kiln. We will consider that Colombian bituminous coal [37] is being burned, with a coal percentage of up to 73%. Equation 1 shows the balance of the combustion process of this bituminous coal considering complete and stoichiometric combustion. Knowing that up to 5000 tons can be burned per day, we will consider a reduced value of 4000 tons per day, equivalent to 46.29 kilograms per second. Then the required mass flow of air is 444.75 kilograms per second, then the exhaust gas flow is 491.04, of which the mass flow of $CO_2$ to the environment is 122.48 kilograms per second. This amount of emissions is significant for the environment, even in developing countries like Peru, where increasing industrialization has polluted the air on a large scale, consequently harming society's well-being in the future. Therefore, this work additionally proposes the implementation of a $CO_2$ capture system that allows to produce urea as a by-process for clinker production in the kiln.

$$\begin{gathered} C_{60.11}H_{47.62}O_{5.69}N_{1.07} + \\ + (69.92O_2 + 263.04N_2) \rightarrow \\ 60.11CO_2 + 23.81\,H_2O + \\ + 0.75SO_2 + 263.57N_2 \end{gathered} \tag{1}$$

To evaluate the Organic Rankine cycle, the outlet temperature of the exhaust gases is important, however, in this type of systems the outlet temperature as well as the mass flow of gases is not constant, there are work peaks in which a greater amount of fuel can be burned. Although during combustion temperatures can reach values between 1400 and 1500 °C, at the kiln outlet temperatures between 800 and 1100 °C can be obtained. However, these gases are usually sent to the clinker preheater and cooler before energy recovery [38, 39]. Currently, there are several studies that use refrigerant gases for organic Rankine cycles for heat recovery, however, in recent years, chemical products have been considered for these cycles, and due to the high outlet temperatures of the exhaust gases, we will consider the following working fluids: Toluene, Decane, D5 (decamethylcyclopentasiloxane) and MD4M

**Table 1.** Technical evaluation

| Systems | | SRC | | ORC | | KAC | | BRC | | Ideal | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical criteria | g | p | gp | p | gp | p | gp | p | gp | p | gp |
| T1 | 4 | 3 | 12 | 3 | 12 | 3 | 12 | 2 | 8 | 4 | 16 |
| T2 | 3 | 2 | 6 | 4 | 12 | 4 | 12 | 2 | 6 | 4 | 12 |
| T3 | 3 | 4 | 12 | 3 | 9 | 2 | 6 | 3 | 9 | 4 | 12 |
| T4 | 2 | 2 | 4 | 4 | 8 | 2 | 4 | 3 | 6 | 4 | 8 |
| Total | | 11 | 34 | 14 | 41 | 11 | 34 | 10 | 29 | 16 | 48 |
| Technical value (gp) | | 0.71 | | 0.85 | | 0.71 | | 0.60 | | 1.00 | |

**Table 2.** Economic evaluation

| Systems | | SRC | | ORC | | KAC | | BRC | | Ideal | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Economic Criteria | g | p | gp | p | gp | p | gp | p | gp | p | gp |
| E1 | 4 | 2 | 8 | 3 | 12 | 2 | 8 | 2 | 8 | 4 | 16 |
| E2 | 3 | 2 | 6 | 3 | 9 | 2 | 6 | 2 | 6 | 4 | 12 |
| E3 | 3 | 3 | 12 | 3 | 12 | 2 | 8 | 2 | 8 | 4 | 16 |
| E4 | 2 | 3 | 9 | 3 | 9 | 2 | 6 | 2 | 6 | 4 | 12 |
| Total | | 10 | 35 | 12 | 42 | 8 | 28 | 8 | 28 | 16 | 56 |
| Economic Value (gp) | | 0.63 | | 0.75 | | 0.50 | | 0.50 | | 1.00 | |

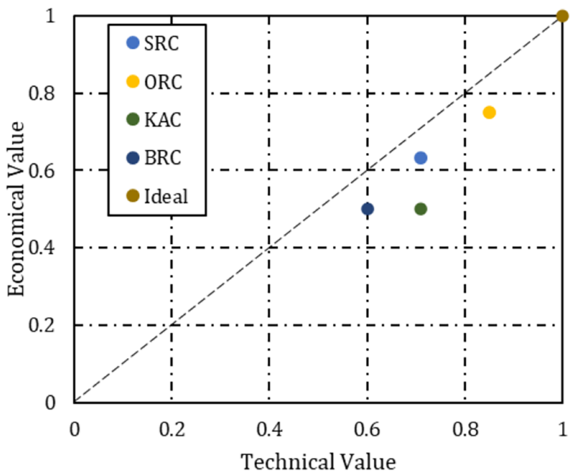


**Figure 1.** Technical and economic evaluation according to VDI 2225. Evaluation of concepts with weighting

(tetradecamethylhexasiloxane). The first two have been studied in ORC systems in several ways, while the last two show future potential in this field [40, 41]. These working fluids have a higher operating temperature than refrigerant gases. To evaluate their operating behavior, we will consider temperatures ranging from 150 °C to 300 °C [42].

Figure 2 shows the schematic of an organic Rankine cycle power plant. The diagram represents a typical waste heat recovery system. The main components are the heat exchanger, which includes the economizer, the evaporator and superheater, the turbine, the condenser, and the pump. The mass flow rate of the working fluid in this cycle will be 180 to 240 kg/s, which was considered in past studies working with these fluids in organic Rankine cycles [42, 43, 44]. Furthermore, the proposed carbon dioxide utilization system can be seen at the top of this diagram. Carbon capture technology is not described in detail in this paper, as it is not the focus of the work. However, it is considered that all $CO_2$ extracted from the process goes to this section. Urea is obtained using a urea system reactor (USR), which requires ammonia and an energy source to produce urea, and water is obtained as a byproduct.

In Peru, the feasibility of waste heat recovery systems is strongly shaped by a mix of local technical conditions, geography, and economic constraints. Electricity prices for large industrial users are relatively high, and generation is still largely centralized, which makes on-site power generation an attractive option for cement producers. In addition, a large number of plants in the southern Andes function at elevations that are nearly 2.500 meters above sea level. Because of the decreased air density in this setting, air-cooled condensers are less efficient, leading to higher condensation temperatures. Because they depend on effective heat rejection, this disadvantages traditional steam Rankine and Kalina cycles, while ORC systems can function even in less ideal sink conditions [45].

Another practical constraint is the availability of water. A number of cement plants are situated in arid regions, making the use of water-intensive cooling systems impractical. Conditions for fuel supply also differ; the majority of plants rely on bituminous coal from Colombia and, occasionally, additional natural gas. Over time, these changes have an impact on kiln exhaust conditions, which facilitates the use of ORC fluids that are stable over a larger temperature range. Lastly, Peru has limited access to low-interest industrial financing, which strongly favors technologies with lower operating and capital costs. When combined, these elements contribute to the explanation of why ORC technology is a better choice for waste heat recovery in this situation [10, 46].

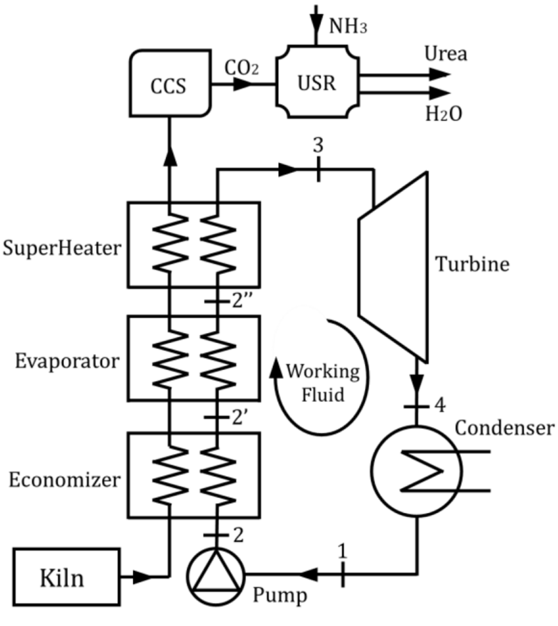


**Figure 2.** ORC System diagram

## Simulation procedure and boundary conditions

The primary procedures of the numerical simulation and the boundary conditions applied in the thermodynamic analysis are explained in this subsection. The temperature ranges, working fluid characteristics, and operating pressures that have been chosen are representative of the typical operating conditions found in southern Peruvian cement plants.

The following section describes the equations for obtaining the parameters resulting from the operation of the organic Rankine cycle. The temperature-entropy diagram corresponding to the work cycle is shown in Figure 3. The fluid is in a liquid state at the condenser outlet and is represented by point 1. Work is supplied to the pump, causing it to raise the pressure from 1 to 2. This pump is considered to operate at an efficiency of 75%. The high-pressure fluid circulates through the economizer from 2 to 2', then through the evaporator from 2' to 2'', and finally the superheater from 2'' to 3. After this superheating, the working fluid expands through the turbine from 3 to 4. Entropy increases during this process. For this procedure, an isentropic efficiency of 80% is considered. During this procedure, the mechanical work that will later be converted into electrical energy is obtained. The working fluid remains superheated at low pressure after the expansion. The fluid finally dissipates heat in the condenser and has a cooling phase to then be at a constant temperature.

Figure 4 shows how the critical temperature, bell width, and entropy variations of bells place them in radically different thermodynamic positions, significantly influencing their performance in a heat recovery ORC. The vaporization/expansion process of siloxanes (such as D5 and MD4M) tends to feature a more vertical bell with lower entropy changes, favoring lower irreversibilities, while toluene exhibits a tendency toward higher entropies and critical temperatures, allowing it to benefit from higher thermal sources. This tendency links fluids with high critical temperatures with higher efficiency, assuming the fluids can be operated close to the critical pressure [47]. A practical limitation to the ideal represented in the theoretical bell is also due to the fact that temperature stability and decomposition can restrict the use of very high operating points, as demonstrated by a comparison with current work on pure siloxanes and mixtures [48]. Finally, it is crucial to note that the optimal performance expected in this type of cycle is determined by the shape of the T-s curve (its slope, its amplitude), which is influenced by changes in evaporation pressure and fluid properties [49].

To calculate the fluid parameters at each operating state, the Engineering Equation Solver software will be used. Initially, to calculate the power required by the pump, it is necessary to know the saturation pressure of the working fluid at the condenser outlet temperature, and the estimated evaporation pressure, which will be the saturation pressure of the fluid at the initial operating temperature delivered by the kiln exhaust gases. Equation 2 shows the required pump power.

$$w_p = \frac{\dot{m}\, v_1\, (P_e - P_1)}{\eta_p} \tag{2}$$

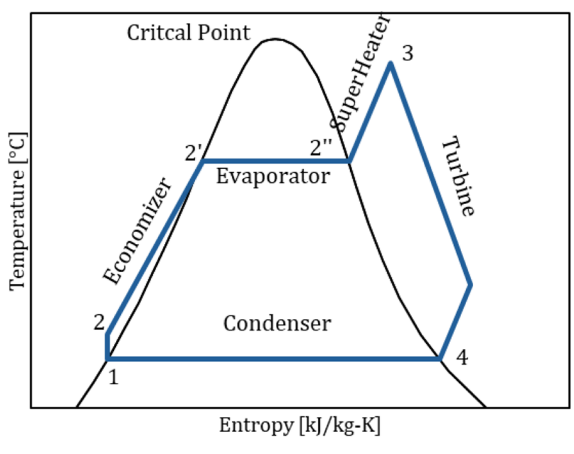


**Figure 3.** T-S diagram for the organic Rankine cycle

Then, the working fluid during its heating stage goes through an isobaric process in which it can be observed that at the economizer outlet the fluid has a quality of 0, then at the evaporator outlet the fluid has a quality of 1, to finally go through a heating in the superheater that is usually variable also by the previously mentioned combustion and environmental conditions, so typical superheating values in these systems are considered from 10 °C to 40 °C [40, 50], to evaluate the cycle performance. Then, the power delivered by the turbine can be observed in Equation 3. The heat delivered to the cycle, the net power and the cycle efficiency are displayed in Equations 4, 5 and 6 respectively.

$$w_t = \dot{m}\,\eta_t\,(h_3 - h_4) \quad (3)$$

$$q_{in} = \dot{m}\,(h_3 - h_2) \quad (4)$$

$$w_{net} = w_t - w_p \quad (5)$$

$$\eta_{ORC} = \frac{w_{net}}{q_{in}} \quad (6)$$

Finally, as shown in Figure 2, urea is produced by the reaction of carbon dioxide and ammonia at high temperature and pressure in a urea system reactor. In the first stage, ammonium carbamate is produced. It is subsequently dehydrated to produce urea [51]. The electrical energy required by this reactor can be estimated using recently analyzed real data [52], obtaining 100 kWh per kg of urea. These two reactions are shown below:

$$2NH_3 + CO_2 \rightarrow NH_2COONH_4 + Heat \quad (7)$$

$$NH_2COONH_4 + Heat \rightarrow Urea + H_2O \quad (8)$$

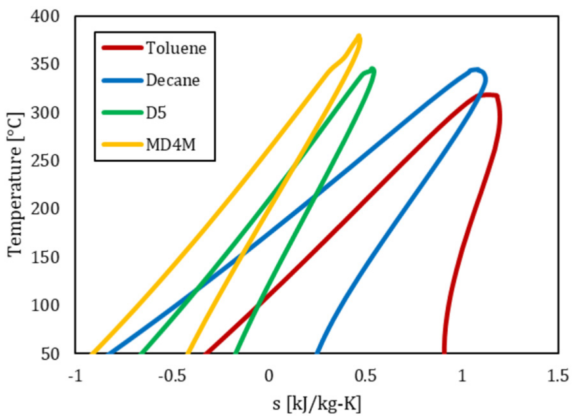


**Figure 4.** Comparison of T-s diagrams of Toluene, decane, D5 and MD4M

The temperature ranges selected for the parametric analysis were defined based on actual operating data obtained from the cement plant. The flue gas temperature after the preheater typically fluctuates between 180 and 320 °C, which justifies the adopted evaporator inlet temperature sweep of 150–300 °C [14, 53]. Similarly, available cooling water at the plant ranges between 20 and 25 °C throughout the year, resulting in practical condensation temperatures of 30–50 °C for air-cooled or hybrid condensers operating at high altitude [54]. It is simpler to connect the simulation setup to the performance trends noted in the analysis when these ranges are used to directly link the parametric results in Sections 3.1–3.4 to actual operating conditions in Peruvian cement plants.

## Implementation recommendations for the Peruvian cement plant

Some specific and useful recommendations for the installation of an ORC-based waste heat recovery system at the cement plant in southern Peru can be made based on the results obtained and the actual conditions at the site. Instead of adhering to a single design principle, the choice of working fluid should take into account the characteristics of each heat source. When evaporation temperatures surpass 250 °C, toluene performs well and produces more power for the kiln exhaust, which reaches higher temperatures. In contrast, the clinker cooler exhaust operates at lower temperatures and is more stable. Because siloxane D5 is more suitable for long-term industrial operation, less hazardous to handle, and still thermally stable, it is a more practical choice in this situation [23, 55].

The analysis's temperature ranges were primarily selected for pragmatic reasons. While maintaining the working fluids within safe operating limits, evaporation temperatures between 250 and 280 °C offer strong performance. For southern Peru, where cooling water is limited and air-cooled systems must function at high altitudes under lower air densities, temperatures of roughly 35 to 40 °C are more practical for condensation. By adhering to these guidelines, the ORC system can function more dependably and the condenser and cooling apparatus won't be overworked [17, 56].

The system is anticipated to produce roughly 2.1 MW of net electrical power from the available waste heat under these circumstances. With this amount of power, the plant would be much more energy independent and would need to purchase far less electricity from the grid. From an economic standpoint, a payback period of nearly 3.2 years is suggested by comparing the anticipated investment and operating costs with the current electricity prices in Peru. The comparatively low operating costs of ORC systems and the high local electricity costs are the primary causes of this outcome. When the system is used in conjunction with $CO_2$ utilization for urea production, the economic outcomes are even more advantageous [57–60].

The suggested ORC system can be installed in the current plant with little disruption to current operations. The ORC units and heat exchangers can be installed alongside the current gas-handling equipment without modifying the kiln itself. Because the system is modular, installation can be carried out with limited downtime, and the investment can be phased if needed. This flexibility makes the proposed solution easier to adopt under real industrial and financial constraints [61, 62].

## RESULTS

In the following section, three temperature parameters that influence the performance of the organic Rankine cycle under evaluation will be discussed. First, the influence of exhaust gas temperature, which directly influences the evaporation pressure of the working fluid. Second, the influence of the superheating temperature delta, which, while additional heat will depend on the heat exchanger design, is important to maintain so that the fluid is not in a liquid state. And third, the influence of condensation temperature, which allows cycle parameters to be adjusted to achieve adequate operating efficiency. Finally, the production of urea as a by-process is discussed. As mentioned in the introduction, it is of interest in regions such as Peru and Latin America as a nitrogen fertilizer for the agricultural sector.

### Influence of the exhaust gas temperature

Figures 5 and 6 shows how the thermodynamic performance of the ORC cycle for the four working fluids studied is directly affected by the exhaust gas temperature of the cement kiln. A constant condensation temperature of 40 °C was considered, and a superheating temperature delta of 20 °C prior to turbine entry. Figure 5 shows how the net specific power output (SNPO) increases almost linearly with the heat source temperature, indicating that more usable energy is available as the thermal gradient between source and sink widens. The ability of toluene to operate efficiently at high temperatures without appreciable deterioration is confirmed by the fact that it exhibits the highest specific power values, followed by decane. In contrast, toluene has a net specific power of more than 190 kJ/kg at 300 °C. Although they continue to function more steadily over a larger temperature range, siloxanes (D5 and MD4M) show a lower SNPO, which is explained by their lower energy density and more constrained use of the sensible heat of gases.

Figure 6 shows a fairly obvious trend: the ORC performs better the hotter the heat source. Higher temperatures merely increase the cycle's ability to convert heat into electricity, so there is nothing surprising here. With efficiencies above 24% at 300 °C, toluene unquestionably triumphs. This occurs as a result of its ability to withstand high temperatures and expand without experiencing condensation problems. Although D5 and MD4M do not achieve the same efficiency levels, they compensate for this in other ways, such as improved chemical stability and lower operating pressures, which are crucial from an operational and safety standpoint. Decane has efficiency values that are relatively constant throughout the temperature range, placing it in the middle. When combined, these findings point to a workable solution: for lower-temperature streams, such as preheater or clinker cooler gases, use D5 or MD4M; for the hotter exhaust from the clinker kiln, use toluene or decane.

These findings highlight the significance of thermal coupling between the heat source and the working fluid since each fluid has a distinct slope on the specific power and efficiency curve. As the exhaust gas temperature rises, fluids like toluene and decane that have a shorter evaporation gradient and a higher critical temperature make better use of the available heat before going over the superheat limit. Conversely, siloxanes have a lower slope on both indicators, indicating less effective heat transfer in heat exchangers at high temperatures, because of their thermophysical properties (lower density and thermal conductivity). However, heat moves through the exchangers more slowly at high temperatures because siloxanes are less dense and don't conduct heat as well. As a result, their efficiency and power don't increase as quickly. However, this

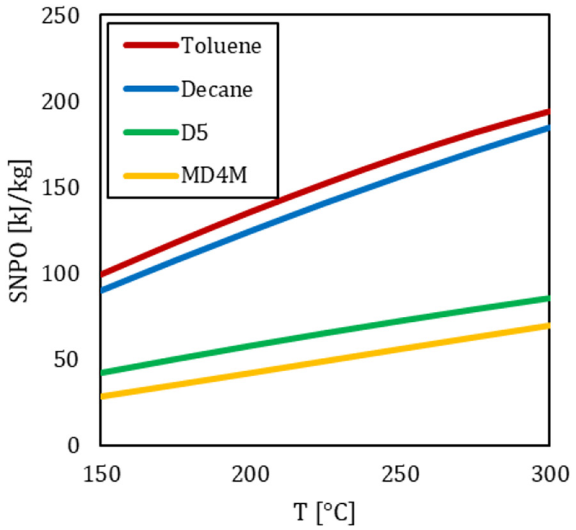


**Figure 5.** Net specific power output of the ORC with varying exhaust gas temperature for the proposed working fluids

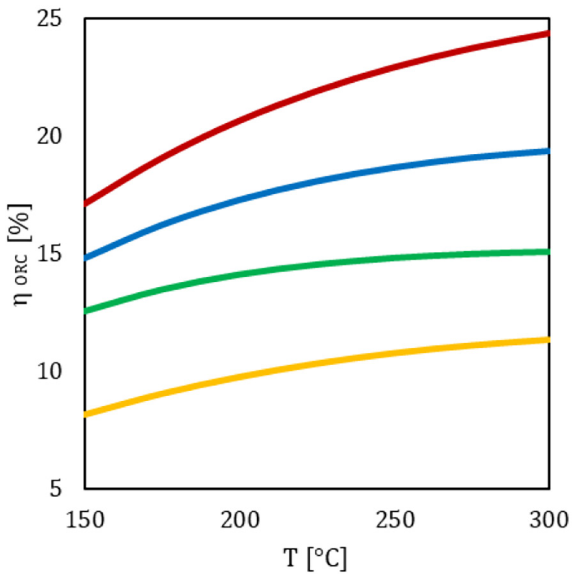


**Figure 6.** Cycle efficiency of the ORC with varying exhaust gas temperature for the proposed working fluids

may actually work to your advantage in the real world. In cement plants, where machines must run continuously, slower heat transfer helps the system function more smoothly and last longer by reducing heat losses and putting less strain on the machinery. Finding a fluid that works well, remains stable under heat, and complements the heat source is ultimately more important than simply achieving the highest efficiency.

When selecting a fluid for industrial use, performance is important, but you also need to consider safety, toxicity, and environmental regulations. Although toluene and decane have the highest power and efficiency, they must be handled in closed systems to prevent vapor or fire hazards due to their flammability. To keep people safe, toluene must remain sealed in the heat exchanger and turbine circuits due to its moderate toxicity. Under typical ORC conditions, decane is still flammable but less toxic. However, siloxanes like D5 and MD4M are far safer; they are non-flammable, hardly toxic, and easily compliant with environmental regulations, making them more suitable for long-term industrial use. Therefore, siloxanes frequently make more sense when safety, regulatory compliance, and long-term reliability are priorities, even though hydrocarbons can provide better thermodynamic performance.

### Influence of superheating temperature difference

Figures 7 and 8 shows how the net specific power and thermal efficiency of the ORC cycle are affected by pre-turbine superheat. An exhaust gas temperature of 250 °C and a constant condensation temperature of 40 °C were considered. Higher superheat promotes steam expansion in the turbine and, consequently, the net work generated, as demonstrated in Figure 7, which shows that the specific power increases slightly with increasing temperature delta for all fluids. Due to their high enthalpy of vaporization and superior thermal stability, toluene and decane exhibit the highest SNPO values and can operate at mild superheats without degradation. Due to their low energy density and being extremely dry fluids, siloxanes D5 and MD4M exhibit smaller increases. Furthermore, usable energy during expansion does not improve significantly with higher superheat. With a delta of 30 °C, toluene can reach a net specific power of 172.3 kJ/kg, maintaining an efficiency very close to 23%.

Figure 8 illustrates a slight decrease in ORC thermal efficiency for all fluids as the temperature delta rises. This effect can be explained by the fact that, although superheating raises net power, it also raises the cycle's energy consumption without correspondingly increasing useful work, which lowers overall efficiency. Fluids with higher negative gradients, like toluene and decane, are more vulnerable to this phenomenon because thermal losses and the turbine's isentropic efficiency restrict its capacity to absorb more heat. Siloxanes show a more gradual decline despite having lower overall efficiencies, suggesting more stable operation under superheat fluctuations.

The results show that, without necessarily increasing overall cycle efficiency, superheat optimization based on fluid type and available exhaust gas temperature is required. A moderate temperature delta (roughly 10–20 °C) seems to be a suitable balance for maximizing net power without significantly lowering thermal efficiency, especially for fluids like toluene and decane. Siloxanes may be a better fit in a cement plant, where maintaining system stability and maximizing waste heat over extended periods of time are crucial, even though they aren't quite as efficient. Conversely, aromatic and linear hydrocarbons perform better during the process when temperatures rise and remain relatively constant.

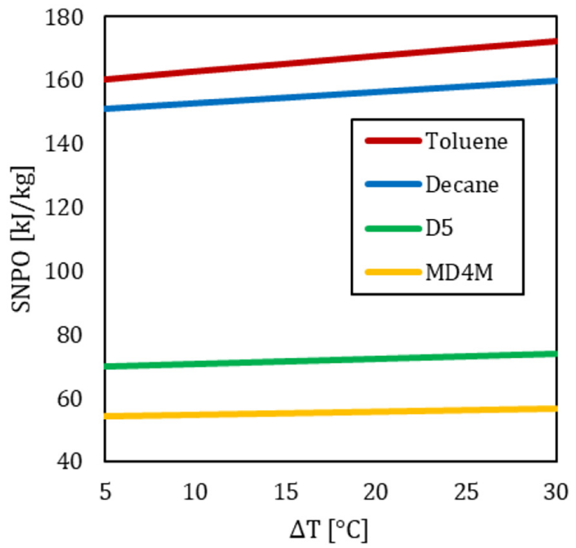


**Figure 7.** Net specific output power of the ORC with the variation of the superheating emperature difference prior to entering the turbine

## Influence of condensation temperature

The impact of condensation temperature on the ORC cycle's net specific power and efficiency while taking into account the four working fluids is depicted in Figures 9 and 10. Prior to the turbine inlet, a superheating delta of 20 °C and an exhaust gas temperature of 250 °C were taken into consideration. Figure 9 displays the net specific power output (SNPO), while Figure 10 displays the ORC cycle's thermal efficiency. For all fluids, as the condensation temperature rises, both the SNPO and the cycle efficiency fall. Since a higher condensation temperature lowers the cycle's effective thermal jump and, thus, its ability to convert heat into useful work, this is consistent with the anticipated thermodynamic behavior. Toluene produces a specific power of 181.2 kJ/kg and an efficiency of 24.23% at 30 °C, whereas MD4M only reaches 59.78 kJ/kg and 11.16%. That is more than twice the efficiency and more than three times the power.

With the highest specific power and thermal efficiency over the entire condensation temperature range, toluene emerges victorious. Stated differently, it exhibits the best thermodynamic performance in the tested conditions. Decane is ranked second, followed by D5 and MD4M, with MD4M having the lowest performance. This demonstrates that, despite the fact that all of these fluids are organic and appropriate for ORC systems, the overall performance actually depends on the particular characteristics of each fluid, such as density, viscosity, heat of vaporization, and thermal stability.

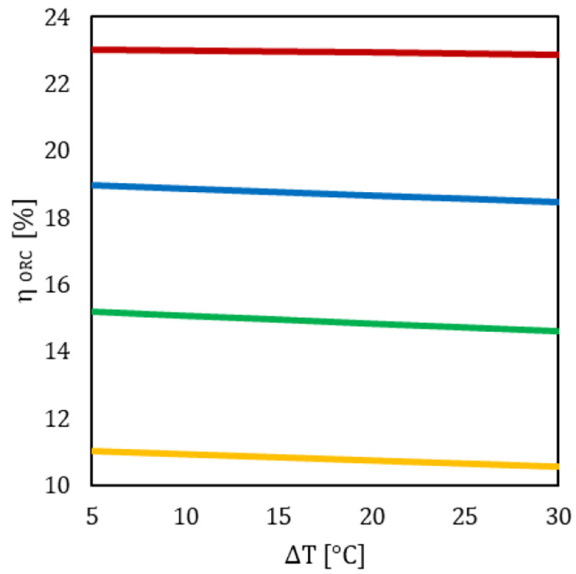


**Figure 8.** Cycle efficiency of the ORC with the variation of the superheating temperature difference prior to entering the turbine

The negative consequences of elevated condensation temperatures underscore the significance of system design in real-world scenarios. In industrial settings like cement plants, where ambient temperatures can reach high levels and cooling water is limited, it is critical to select a fluid that maintains a satisfactory level of efficiency. Even though toluene performs exceptionally well, other factors like cost, toxicity, and safety need to be taken into account. Thus, selecting the best fluid necessitates striking a balance between

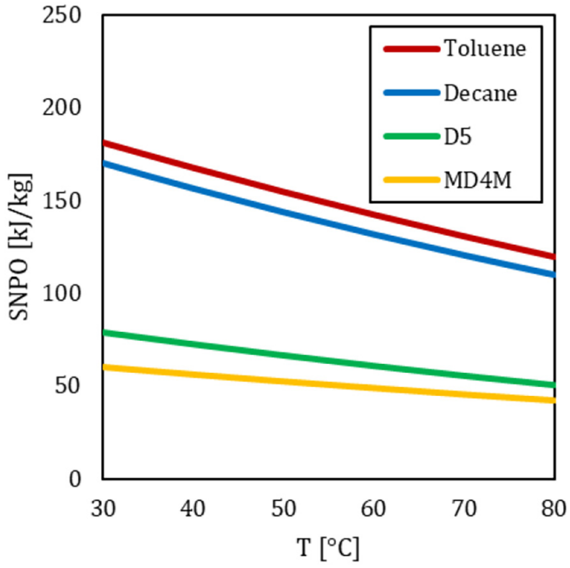


**Figure 9.** Net specific output power of the ORCwith the variation of the cycle condensation temperature

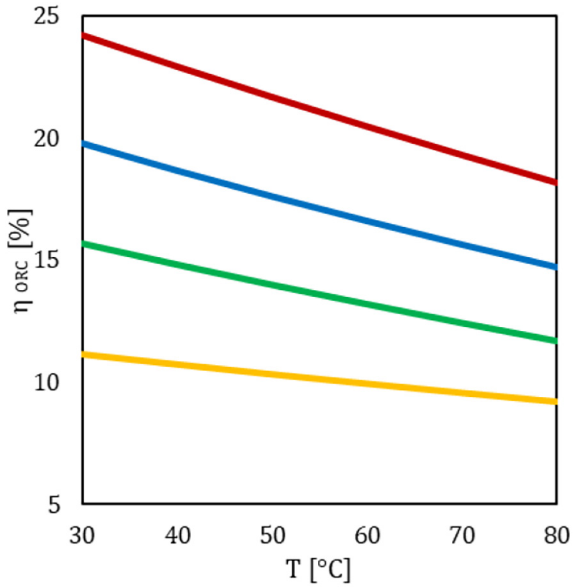


**Figure 10.** Cycle efficiency of the ORC with the variation of the cycle condensation temperature

operational considerations and thermodynamic performance, particularly in harsh settings like cement production processes.

## Urea production

The initiative to implement urea production as a by-process lies in the fact that agriculture in South America has shown a systematic growth trend in recent decades, mainly due to increased productivity and demand not only in the region but also abroad [63, 64]. Specifically, the Peruvian economy is largely based on agriculture and relies heavily on fertilizers, importing around 90% of synthetic fertilizers [65]. Peru is responsible for around 600 to 700 kilotons of nutrients per year, amounts that continue to grow. Furthermore, the manufacture and transportation of fertilizers to Peru represent a significant contribution to $CO_2$ emissions [66]. Likewise, recent conflicts in the world have significantly impacted the agricultural productivity of Peruvian farmers, as they have limited capacity to cope with the increase in fertilizer prices [65]. Therefore, initiatives that promote fertilizer production, in this case as a by-process, are of great support for the industrial sector to consider, with the goal of fostering long-term sustainable development.

According to the chemical balance described in the methodology section, the mass balance in the urea production process for a constant urea production, considering a carbon dioxide mass flow rate of 122.48 kg/s. This results in a constant urea production of 167.15 kg/s. However, this amount is excessive, as it is equivalent to 15,920 tons per day. Therefore, the urea reactor alone can be considered to operate for 6 hours per day, which would produce 3,980 tons of urea per day. The $CO_2$ must also be kept in the capture and storage system. It's worth noting that in recent years, many alternatives have been evaluated for the use of $CO_2$ in other applications, not only as an input for producing certain materials, but also in the petrochemical and food industries, for example.

From a climate-policy perspective, integrating $CO_2$ capture with urea synthesis may enable the cement plant to qualify for carbon offset mechanisms under UNFCCC-aligned voluntary markets. Unlike the previous classification used, the appropriate terminology refers to "carbon offsets" or participation in broader "carbon reduction mechanisms" [67]. The potential eligibility would depend solely on verified $CO_2$ utilization that displaces conventional fossil-based urea production. Although it's not the primary goal here, producing urea from the captured $CO_2$ could generate some additional income and provide a pleasant environmental boost to the energy recovery system.

Making urea on-site from captured $CO_2$ could be a nice little revenue boost, as urea sells for about USD 500 to 650 per ton in Peru. Although suppliers and project size will undoubtedly affect costs, research indicates that these systems can be economical and even partially offset the plant's operating expenses. In essence, using captured $CO_2$ in this manner benefits both the environment and the economy.

The urea system is set up to be downstream from the $CO_2$ capture unit, so it doesn't get in the way of making clinker or the kiln. It is modular, meaning it can take in purified $CO_2$ and ammonia without changing the flow of gases, combustion, or process temperatures. The parts, such as the compact reactor, $CO_2$ conditioning module, and ammonia interface, can be added to existing cement plants without any problems. Research indicates that this configuration can be implemented without disrupting standard operations. The urea synthesis section is a modular add-on that gets purified $CO_2$ and an external ammonia feed without changing the flow of gas, the conditions for combustion, or the temperatures of the process. The required auxiliary components – such as a compact synthesis reactor, $CO_2$ conditioning module, and ammonia supply interface – are compatible with standard cement-plant layouts and can be installed parallel to the existing gas-handling line. Recent $CO_2$-to-urea integration studies indicate that such modular configurations can be incorporated without affecting core industrial processes and are designed to minimize operational disruptions during installation [29, 30].

## CONCLUSIONS

In this study, an energy generation system with waste heat recovery was analyzed through a thermodynamic cycle, considering a kiln in a cement plant in southern Peru as a case study. Based on an analysis conducted in accordance with VDI 2225 regulations, the organic Rankine cycle was considered preferable over other thermodynamic cycles through a technical and economic evaluation. Four working fluids were evaluated: toluene, decane, D5, and MD4M, which have a mean critical temperature close to, and higher than, that of the refrigerant gases. The net specific power and cycle efficiency were evaluated, influenced by the exhaust gas temperature, the superheating delta temperature prior to entering the turbine, and the cycle condensation temperature. First, it can be seen that increasing exhaust gas temperature increases the net specific power and cycle efficiency for all fluids; however, in the case of toluene and decane, this increase is greater than in D5 and MD4M. It is then concluded that the superheating temperature delta has little influence on the net specific power and efficiency within the typical operating ranges of these cycles. Condensation temperature does influence the study parameters, with lower efficiencies and power obtained at higher condensation temperatures in the cycle. Generally, toluene and decane performed better, with toluene presenting an efficiency of 23%. However, siloxanes D5 and MD4M are currently under study. Therefore, analyses that improve their energy capacity may consider them as potential fluids, as they have greater stability, lower toxicity, and lower environmental impact. Finally, urea production was proposed as a subprocess through carbon capture from cement kiln exhaust gases. The goal is to generate a sufficient amount of urea as fertilizer for Peru as a sustainable solution for the agricultural sector in the region. This study theoretically demonstrates the implementation of a heat recovery system through an organic Rankine cycle at a cement plant, considering the use of carbon dioxide from the exhaust gases to produce urea as a by-product.

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