

# Integrated assessment of the energy, environmental, and economic performance of the boiler at the animal processing plant in Chipaque, Cundinamarca

## Evaluación integrada del desempeño energético, ambiental y económico de la caldera de la planta de beneficio animal de Chipaque, Cundinamarca

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### Abstract

In the current context, the application of energy efficiency principles is crucial for reducing operational and maintenance costs, as well as minimizing environmental impacts associated with the production of goods and services. This research evaluated the energy efficiency of the boiler installed at the animal processing plant in the municipality of Chipaque, Cundinamarca. Based on the current operating conditions and parameters of the unit, energy balances were developed to determine efficiency percentages, and an alternative was proposed to enhance its performance through the installation of an economizer. This system enables the recovery of waste heat from combustion gases, improving the thermal efficiency up to 79%. An environmental and economic assessment was also conducted, emphasizing the comparison of environmental impact scenarios before and after the installation of the economizer. Results showed a reduction in the percentage distribution of environmental impacts within the categories of climate change and depletion of water bodies, from 100% to 81.7% and 75%, respectively. Additionally, fuel savings were estimated at approximately COP \$3,800,000 with a payback period of around seven months.

**Keywords:** boiler, climate change, economizer, energy balance, energy efficiency.

### Resumen

En el contexto actual, la aplicación de principios de eficiencia energética es determinante para la reducción de costos de operación, mantenimiento e impactos ambientales en la producción de bienes y servicios. La investigación evaluó la eficiencia energética de la caldera instalada en la planta de beneficio animal del municipio de Chipaque, Cundinamarca; con base a las condiciones y parámetros actuales de dicha unidad, se desarrollaron balances energéticos para establecer porcentajes de eficiencia energética, y se consolidó una alternativa para su desempeño, basada en la instalación de un economizador, que permite el aprovechamiento del calor de los gases de combustión, mejorando el rendimiento térmico hasta el 79%. Se realizó una evaluación ambiental y económica, destacándose la comparación de escenarios de impacto ambiental antes y después de la instalación del economizador, con una reducción de la distribución porcentual de los impactos ambientales en las categorías de cambio climático y disminución de los cuerpos de agua, del 100% a 81,7% y 75%, respectivamente; así como el ahorro del combustible, que corresponde a un valor cercano a los \$3.800.000 COP y un tiempo de retorno de inversión cercano a los 7 meses.

**Palabras claves:** balance energético, caldera, cambio climático, economizador, eficiencia energética.

## 1. Introduction

The development of production processes involves the use of various natural and energy resources, which constitute a fundamental part of each unit operation. Industrial productivity in the manufacture of goods and services can be measured in terms of energy efficiency. Currently, energy efficiency is linked to multiple sustainability methodologies, as well as to environmental legislation in several countries worldwide, contributing to the reduction of greenhouse gas (GHG) emissions, the conservation of raw materials, lower operational and maintenance costs, and the mitigation of environmental aspects and impacts [1].

Among the most widely used industrial equipment in production processes are boilers. These units play a vital role in thermodynamic cycles, enabling the generation of steam required for numerous operations, with extensive applications in sectors such as healthcare, food and beverage production, steel, cement, and ceramics. Boilers are used in heating, sterilization, and disinfection systems, and in the generation of electrical power through turbines and thermodynamic power cycles [2].

Over time, boilers have been classified into water-tube and fire-tube systems. The former feature a technological configuration that allows water circulation inside the boiler until steam is produced, while combustion gases are discharged into the atmosphere [3]. In contrast, in fire-tube boilers, combustion gases flow through internal tubes, transferring heat to the surrounding water until it reaches saturation [4].

The selection of the boiler type for steam generation in production processes must consider specific operational needs, site location, pressure and water levels, combustion chamber design, and exhaust gas configuration, including control systems [3].

The performance of a boiler, measured in terms of energy efficiency, determines the degree of water evaporation and/or the percentage of heat transferred from the fuel to the heat-transfer fluid (i.e., water), also considering the fuel's calorific value. Studies on boiler energy efficiency encompass a wide range of equipment types, fuels, and thermal modeling approaches. Park et al. conducted research focused on determining optimal operational conditions for boilers, using a computational model to measure energy efficiency across combustion stages [5]. Similarly, estimating the amount of heat transferable to water per unit mass and calorific value of different fuels allows for efficiency assessment. Ke Ji et al. highlighted the importance of fuel loading ratios and their effect on combustion stability, thermal efficiency, and the approximate volume of combustion gases produced [6].

Furthermore, several methods have been proposed to evaluate the thermal performance of boilers regardless of the type of fuel employed. Jiménez, R. et al. proposed the use of thermographic cameras, combustion gas analyzers, and flow meters to determine boiler efficiency through temperature curves and heat loss measurements to the environment [7].

However, the installation of additional thermodynamic equipment aligned with steam generation can significantly improve boiler energy efficiency. Fritzson & Berntsson proposed the implementation of heat exchangers and heat pumps to preheat water and/or air injections in boilers, thereby reducing fuel consumption and, consequently, GHG emissions [8].

In addition, reference frameworks have been established to guide environmental management and eco-efficiency in the meat-processing industry, to which the animal processing plant belongs. Iten et al. developed strategies that include the installation of cooling systems, recovery of organic residues, integration of renewable energy sources, and diversification of boiler

fuels, as tools to comply with environmental standards and improve thermal process performance [2].

This study evaluates the energy efficiency of the boiler at the animal processing plant, part of Colombia's food sector and located in the municipality of Chipaque, Cundinamarca. The analysis compares current operating conditions with those following the installation of an economizer, which enables the recovery of heat from combustion gases through an industrial heat exchanger. Additionally, the study includes an environmental and economic assessment of the steam generator, identifying environmental impacts, fuel savings, and the investment payback period, with the aim of enhancing energy efficiency and optimizing industrial performance.

## 2. Methodology

### 2.1. Current performance of the boiler

The initial assessment of the boiler's energy efficiency was based on its operating variables. A technical visit to the plant was conducted to collect data related to the water supply system, fuel consumption, operating pressure, and the type of burner installed. Based on the information obtained, the boiler's current performance efficiency was determined through energy balance calculations using fuel and water flow rates, allowing the estimation of the amount of heat transferred from the fuel to the system [9]. The proposed mathematical model for the determination of energy efficiency is as follows:

$$Q_{rxn-c} = \sum mCp(T_f - T_i)_{Outputs} - \sum mCp(T_f - T_i)_{Inputs} \quad (1)$$

Where:

**Qcg:** heat released by the combustion gases, in kJ/day.

**Qra:** heat absorbed by the water, in kJ/day.

**msteam:** steam flow rate, in kg/day.

**hf:** enthalpy at the saturated liquid point, in (kJ/kg).

**hg:** enthalpy at the saturated vapor point, in (kJ/kg).

The heat of the combustion reaction corresponds to the product of the fuel's calorific value and its mass supplied to the boiler, as expressed in the following equation:

$$Q_{rxn-c} = PC \times m \quad (3)$$

Where:

**Qrxn-c:** heat of the combustion reaction, in kJ/day.

**PC:** calorific value of the fuel, in kJ/kmol.

**m:** mass of gases, in kmol/day.

The energy efficiency of the boiler is given by:

$$EEb = \frac{Qra}{PC \times m} \times 100 \quad (4)$$

Where:

**EEb:** energy efficiency of the boiler, in (%).

**Qra:** heat absorbed by the water, in kJ/day.

**PC:** calorific value of the fuel, in kJ/kmol.

**m:** mass of gases, in kmol/day.

The starting point for these calculations corresponds to the combustion reaction, which must be defined according to the type of fuel used in the boiler.

## 2.2. Proposal for Improving Energy Efficiency

The increase in the energy efficiency of the boiler within the production process is ensured through the installation of an economizer, which utilizes the exhaust heat from the combustion gases to preheat the feedwater entering the boiler for steam generation. The heat recovered from the combustion gases of the boiler was calculated to determine the improvement in energy efficiency for the new integrated system (boiler and economizer), using the following equation:

$$IEE_b = \frac{Q_{ra-sp}}{Q_{rc-p}} \quad (5)$$

Where:

**IEEb:** increase in the boiler's energy efficiency, as a decimal fraction.

**Qra-sp:** heat absorbed by the water without the economizer, in (kJ/day).

**Qra-p:** heat absorbed by the water with the economizer, in (kJ/day).

The implementation of the economizer is presented in a theoretical framework, as the advanced design of this heat exchanger and its operational integration within the plant are beyond the scope of the present study. Nevertheless, the information obtained provides a foundation for future research aimed at further improving the boiler's energy efficiency.

## 2.3. Environmental and economic assessment of steam generation

Two alternatives were considered for the environmental evaluation. Using SimaPro® software, the environmental implications before and after the installation of the economizer in the boiler system were assessed.

The modeling process enabled a life cycle analysis (LCA) of the industrial equipment operation, accounting for all resource inputs and combustion products.

The objective of this assessment was to determine the percentage reduction in environmental impacts across the categories modeled in the software, following the Environmental Product Declaration (EPD) methodology. The analyzed impact categories included: acidification (AC), eutrophication (ET), global warming (GW), ozone layer depletion (OLD), photochemical oxidant formation (PO), abiotic depletion due to fossil fuel use (ADFF), and progressive water scarcity (WS). The economic evaluation was focused on determining the fuel savings achieved by installing the economizer in the boiler system. The first part of the assessment was carried out by estimating the increase in the boiler's energy efficiency using Equation (5), and subsequently calculating the corresponding fuel cost savings. The calculation was based on the reference price per cubic meter of fuel consumed in industrial activities in the municipality of Chipaque, Cundinamarca [10], and the savings by the model proposed by A. P. Sánchez et al [16].

## 3. Results and discussion

According to the approach established in the methodology, the results and their corresponding analysis are presented in the following sections.

### 3.1. Current performance of the boiler

The recorded operating parameters are shown in Table 1.

**Table 1.** Summary of Boiler Operating Parameters.

Boiler operating parameters	Values
Natural gas supply (m <sup>3</sup> /day)	83.33

Boiler operating parameters	Values
Water flow rate (L/day)	600
Operating boiler pressure (kPa)	500
Ambient temperature (°C)	14

The on-site inspection at the animal processing plant identified that the boiler is installed to carry out disinfection activities for hides and meat within the production process, linked to steam generation. The boiler operates on natural gas, and its operation is carried out without adherence to a standardized procedure. As a result, the current fuel cost is relatively high, reaching approximately five million Colombian pesos (COP) per month.

The boiler corresponds to model CV-3015-C, manufactured by Colmáquinas in 1994, with a rated capacity of 30 BHP/h and a design pressure of 150 psi. The input and output flows of the boiler are presented in Figure 1.



**Figure 1.** Boiler of the animal processing plant.

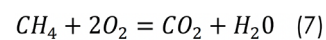
The composition of natural gas consists predominantly of methane; therefore, the combustion reaction of methane was used as the basis for determining the input and output streams of the boiler within the production process. The boiler is equipped with an atmospheric burner, and an excess air factor of 65% was considered, as typically applied to this type of burner [11]. To determine the mass of gas entering the boiler, based on the combustion reaction, the ideal gas equation was employed.

$$n = \frac{PV}{RT} \quad (6)$$

Considering that R corresponds to the gas constant (8.31 kJ/kmol·K), the ambient temperature of the plant is 287.15 K, and the gas injection pressure is under standard conditions, with a volumetric flow rate of 83.33 m<sup>3</sup>/day of natural gas, the methane mass is determined as follows:

$$n = \frac{101.3 \text{ KPa} \times 83.33 \text{ m}^3}{\frac{8.31 \text{ kJ}}{\text{kmol}^\circ\text{K}} \times 287.15^\circ\text{K}} = 3.51 \text{ kmol CH}_4$$

Based on the methane mass, the stoichiometry of the reaction shown in Equation (7) was established to determine the input of oxygen and nitrogen, as well as their corresponding outputs, along with carbon dioxide and water. The results are summarized in Table 2.



**Table 2.** Inputs and Outputs in the Boiler for the Energy Balance.

Type of flow	Compound/Element	Kmol
Inputs	CH <sub>4</sub>	3.51
	O <sub>2</sub>	11.59
	N <sub>2</sub>	43.61

Type of flow	Compound/Element	Kmol
Outputs	CO <sub>2</sub>	3.51
	H <sub>2</sub> O	7.03
	O <sub>2</sub>	4.57
	N <sub>2</sub>	43.61

Based on Equation (1) and considering that the initial temperature is 14 °C, it is necessary to calculate the temperature of the dry flue gases in the boiler. For this purpose, an iterative process was carried out to determine the heat capacity of the exhaust gases, solving for the final gas temperature using Equation (8).

$$T_f = \frac{LHV_{CH_4} \times m_{CH_4}}{(m_{CpCO_2} + m_{CpO_2} + m_{CpH_2O} + m_{CpN_2})} + 14^\circ C \quad (8)$$

A final temperature of 2300 °C is assumed, which should be averaged with the ambient temperature and converted from degrees Celsius to Kelvin, since the temperature used for the specific heat capacity of the exhaust gases is expressed in Kelvin, as follows:

$$IT = \frac{T_{f\text{assumed}} + T_{amb}}{2} + 273,15 \quad (9)$$

Table 3 summarizes the iterative temperature (IT) calculations, which converge to a final gas temperature of 1517.74 °C (1824.89 K) under the stated boiler operating conditions.

**Table 3.** Iterated temperatures for the energy balance model.

T assumed (°C)	IT (°C)
2300	1,433.69
1433.69	1,529.58
1529.58	1,515.78

T assumed (°C)	IT (°C)
1515.78	1,517.74

To calculate the heat released by the combustion gases, only the sum of the outlet streams is considered. Since the actual temperature of the combustion gases (Ti) is not known, it must be estimated using Equation (2), which describes the transformation of water into steam. The enthalpies hg and hf are obtained from the thermodynamic property tables of water, considering the atmospheric pressure and ambient temperature at the location of the animal processing plant, 101.3 kPa and 14 °C [13], together with the boiler's operating gauge pressure, estimated at 500 kPa. Thus, the total pressure is 601.3 kPa, equivalent to 0.6013 MPa. Hg is estimated at 2,756.89 kJ/kg and hf at 58.79 kJ/kg. Considering that the 600 L/day of feedwater supplied to the boiler correspond to 600 kg/day, the heat released by the combustion gases is obtained using Equation (2).

$$Q_{cg} = 600 \frac{kg}{d} \times \frac{(2756,89 - 58,79)kJ}{kg} = 1,618,858.2 \frac{kJ}{d}$$

Based on the formulation of the model equations, the energy efficiency of the boiler under current operating conditions, as determined using Equation (4), is calculated to be:

$$EEb = \frac{1,618,858.2 \text{ kJ/día}}{890,360 \frac{kJ}{kmol} \times 3.51 \frac{kmol}{día}} \times 100 = 51.8\%$$

### 3.2. Proposal for Improving Energy Efficiency

The boiler operates with a calculated thermal efficiency of 51.36%. Therefore, the installation of an economizer is proposed to recover the heat from the flue gas outlet and use it to preheat the boiler feedwater, thereby reducing natural gas consumption.

Consequently, the heat transferred from the flue gases to the feedwater entering the economizer, representing the preheated water enthalpy is quantified based on Equation (1). For this calculation, only the outlet streams of the boiler are considered, with the temperature order inverted, since the final temperature corresponds to the exhaust gas outlet. According to design and safety criteria for heat recovery systems, the minimum flue gas outlet temperature must not fall below 121 °C [11]; however, to ensure operational stability and prevent acid dew point condensation within the economizer, a conservative reference temperature of 130 °C is adopted. The heat calculated from Equation (1), considering exclusively the contribution of the exhaust gases, corresponds to 1,267,854.28 kJ/d.

Based on the thermodynamic correlation between the enthalpic input of the feedwater prior to preheating and the enthalpic gain after preheating, the incremental improvement in the boiler's overall energy efficiency can be quantitatively determined by applying Equation (5) as expressed below:

$$IEE_b = \frac{1,618,858.2 \text{ kJ/d}}{1,267,854.28 \text{ kJ/d}} = 1.28$$

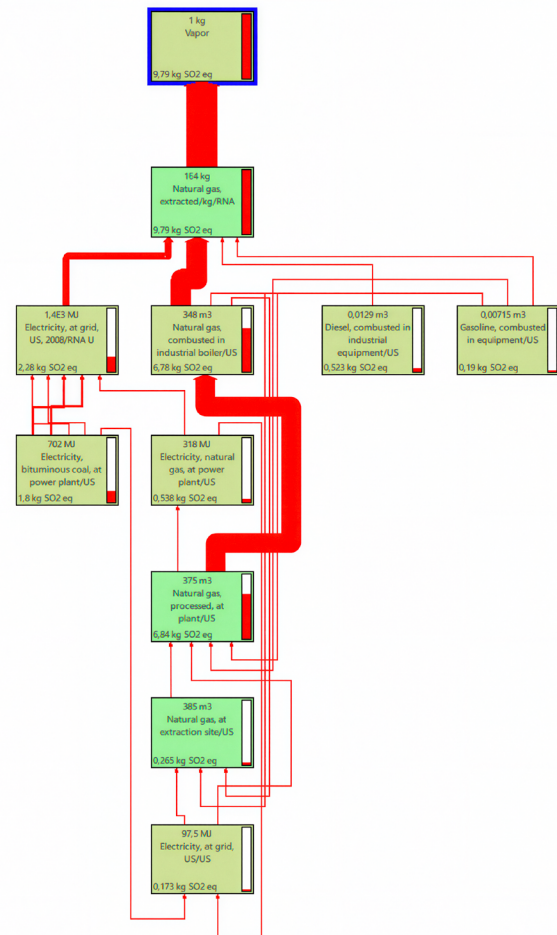
With the implementation of the economizer, the boiler's thermal efficiency would increase from 51.8% to 66.3%, representing a substantial enhancement in overall energy conversion performance and heat recovery effectiveness within the steam generation system.

### 3.3. Environmental and Economic Assessment of Steam Generation

Using the SimaPro® software, the environmental impacts associated with the boiler's operation were quantified under two distinct scenarios: without economizer and with economizer.

The environmental assessment encompassed the analysis of the potential environmental

implications involved in producing 1 kg of steam within the boiler system, following the pathway outlined below.

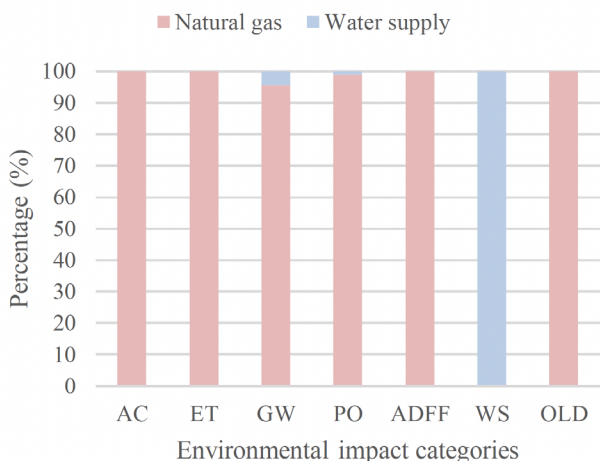


**Figure 2.** Environmental assessment pathway incorporating life-cycle considerations.

Once the assessment pathway was established, which considers the life-cycle stages of natural gas consumption and the use of electrical energy during the boiler's operation, the EPD methodology was applied. The results for the environmental impact categories are presented in Figures 3 and 4.

The environmental impacts associated with natural gas are entirely concentrated (100%) within the AC, ADFF ET, and OLD categories, whereas water consumption for steam generation accounts for the total impact

within the WS category. In the GW category, water use in the boiler contributes 4.44% to the total impact, while natural gas accounts for 95.6%. PO is distributed as 99% for natural gas and 1% for water.

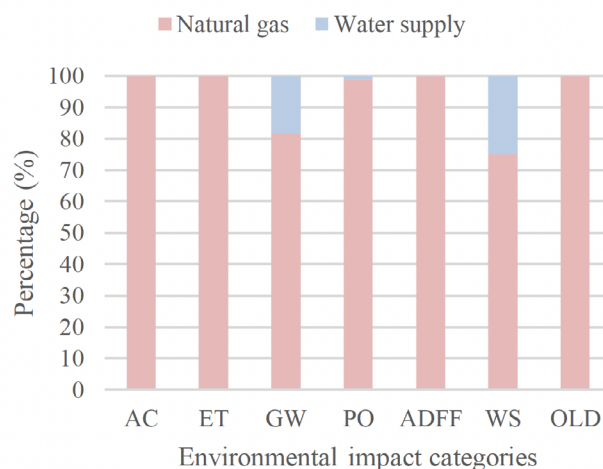


**Figure 3.** Environmental impact assessment of the boiler under baseline operating conditions.

The composition of natural gas, derived from conventional hydrocarbons, results in combustion products containing GHG, which generate a range of environmental implications associated with climate change. Combustion by-products such as CO<sub>2</sub> can contribute to the acidification of aquatic systems and to the degradation of abiotic media due to secondary chemical reactions triggered within these environments [17]. Likewise, the predominant impact related to water use in the boiler is linked to water scarcity, directly influencing the depletion of this natural resource [18] during steam production in the animal processing plant.

In contrast to the boiler operation scenario without the economizer, the environmental assessment conducted after the installation of this heat exchanger shows notable variations across several impact categories. There is a reduction in the contribution of natural gas use to the GW category, decreasing from 95.6% to 81.7%, accompanied by an increase

in the contribution of water use from 4.44% to 18.3%. Since the installation of the economizer decreases the volume of water required for steam generation in the meat processing lines, the impact within the WS category decreases from 100% (fully attributed to water use) to 75%. The impact categories corresponding to AC, ET, PO, ADF, and OLD maintain the same proportional distribution of environmental impacts observed during boiler operation without the economizer.



**Figure 4.** Environmental impact assessment of the boiler operating with economizer integration.

Fuel savings were determined based on the water flow rate in the boiler before and after undergoing the preheating process. The heat content of the water at each stage was calculated using Equation (2), ensuring that the preheating process raised the water temperature to 80 °C and increasing the water supply to 6000L/d. Table 4 summarizes the variables required for calculating the natural gas volume.

By applying Equation (6) and considering the CH<sub>4</sub> mass expressed in kmol, the estimated natural gas consumption of the boiler, derived from the stoichiometric reactions, is 1,324.08 m<sup>3</sup>/month. Fuel savings were determined by multiplying the calculated natural gas volume by the reported unit cost of the service, which amounts to \$2,842.56 COP [10].

**Table 4.** Variables for natural gas volume determination.

Variables	Value
Qra-sp (kJ/kg)	23,794,796.7
Qra-p (kJ/kg)	22,078,100.7
mCH <sub>4</sub> /month (kg CH <sub>4</sub> /month)	893.14
mCH <sub>4</sub> (kmol)	55.82

The resulting fuel savings with the installation of the economizer are estimated at \$ 3,763,776.84 COP per month. In Colombia, economizers are commercially available through engineering firms that conduct feasibility assessments and cost analyses related to the implementation of such industrial-scale heat exchangers. According to the catalog of HRC Ingeniería, the estimated cost of an economizer is approximately \$26.5 million COP [15]. Based on this cost and the monthly fuel savings, the payback period of the potential investment was calculated using the model proposed by A. P. Sánchez et al. [16], as follows:

$$Payback = \frac{Investment}{Savings} \quad (10)$$

The payback period related to the installation of the economizer is 7 months.

## 4. Conclusions

The development of the mathematical model, based on the principles of thermodynamics, allowed for the calculation of the energy efficiency of the boiler at the animal processing plant in Chipaque, Cundinamarca, yielding a value of 51.8%. Furthermore, the analysis demonstrated that the proposed installation of an economizer for the combustion gases of the process increases the thermal efficiency to 66.3%. It is important to note that an advanced economizer design could further enhance the proposed system, contributing

to improved boiler performance in future operations.

The environmental assessment highlights the impact of natural gas consumption on categories such as acidification (AC), eutrophication (ET), photochemical oxidant formation (PO), and abiotic depletion due to fossil fuel use (ADFF), where the percentage distribution reaches 100%. With the implementation of the economizer, there is a reduction in the environmental impact associated with progressive water scarcity (WS), decreasing from 100% to 75%, alongside a reduction in the global warming (GW) category, from 95.6% to 81.7%, attributed to natural gas use. Additionally, technological upgrading can be considered, such as the future replacement of the boiler, provided the necessary resources are available for the acquisition of a new steam generation unit at the plant.

The fuel savings resulting from the economizer installation represent a significant reduction, approximately 50%, in the monthly cost of this utility service for the facility. This evidence underscores that the implementation of energy efficiency strategies in the production of goods and services yields tangible economic benefits for organizations seeking to optimize their operational processes.

Although the investment required for economizer installation may exceed the amount reported in this study, the application of energy efficiency principles ensures that the payback period can be achieved within months following the commissioning of the industrial equipment. Specifically, for the animal processing plant, the investment in the economizer is recovered in approximately 7 months.

Thus, the optimization of production processes exemplifies how industrial operations can be linked with academic research to enhance the generation of goods and services, improving the thermal performance of

critical equipment, such as steam generators or boilers, which play a fundamental role in modern industrial systems.

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