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ORIGINAL ARTICLE

Thermoeconomic analysis of the IWERS system for steam heat recovery from bakery ovens

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Abstract

The integrated waste energy recovery system (IWERS) recovers heat from bakery ovens in supermarkets and other commercial facilities to heat domestic hot water, resulting in energy savings. This article presents a thermoeconomic analysis of the system's operation in a supermarket over the course of 1 year. The study shows that exergy destruction in IWERS is directly proportional to ambient temperature. During the hottest months of the year, IWERS experiences a 4% decrease in exergy performance, while the exergy unit cost of the product increases by up to 4.2%. Additionally, the steam condenser is responsible for the highest relative exergy destruction, reaching almost 45%. Moreover, the addition of equipment upstream of the process increases the exergy cost of production due to the destruction of exergy in the equipment. These results provide valuable information with important implications for energy efficiency, economic savings, and sustainability. Improving system efficiency would generate substantial benefits in energy savings, economic savings, and environmental impact for all commercial and industrial establishments that use bakery ovens.

KEYWORDS

bakery oven, exergetic efficiency, exergetic evaluation, heat recovery, integrated waste energy recovery systems, thermoeconomic

1 | INTRODUCTION

Thermoeconomics is a field that combines thermodynamic principles with economic analysis. It aims to optimize the design and operation of thermal systems by applying thermodynamic principles and economic parameters.[1,2] The laws of statistical mechanics are applied to economic theory, treating economic value as a physical system.[3] Furthermore, the field of thermoeconomics involves the development and application of exergy and economy analysis, also known as exergoeconomics.[2] This field is a powerful tool for analyzing, diagnosing, and optimizing energy systems, providing a deeper understanding of how human societies obtain and use energy.[4] Numerous scientific articles and research studies have contributed to the advancement of thermoeconomics, demonstrating its potential in optimizing and accounting for the costs of energy systems.[5] Thermoeconomics has become an essential area of research due to the increasing demand for natural and energetic resources and the signs of global warming. It aims to provide advanced tools to solve complex energy problems. Thus, this discipline combines thermodynamics and economics, providing a unique framework for analyzing energy systems. The exergetic cost theory is a key methodology in this field, introducing the concept of exergetic cost to the thermoeconomic domain.[6] This approach has significantly contributed to the comprehensive evaluation and optimization of energy systems, reflecting the intrinsic link between energy and economic considerations. The integration of thermodynamic principles with economic analysis has become increasingly important in the study of systems and processes, especially in the context of rising global energy demands and the need for sustainable resource management.

The field of thermoeconomics has experienced significant advancements in recent years. A special issue in the journal Entropy was dedicated to collecting original papers focused on thermoeconomic analysis, providing an overview of current research in the field and its potential applications.[7] Furthermore, various research studies have demonstrated the effectiveness of thermoeconomic optimization and cost accounting in evaluating energy systems.[5] The integration of thermodynamic principles with economic analysis in the study of energy systems has become increasingly important. This is particularly relevant in the context of rising global energy demands and the need for sustainable resource management.[8] Therefore, thermoeconomic analysis is useful for addressing complex energy problems.

The thermoeconomics literature classifies articles based on the facilities analyzed, covering a wide range of systems and facilities. The classification can be summarized as follows:

1. *Energy systems*: Several articles focus on the thermoeconomic analysis and optimization of energy systems, demonstrating the application of thermoeconomics in this field.[8–10]
2. *Cogeneration systems*: Research has been conducted on advanced cogeneration systems, particularly in the context of buildings, with an emphasis on the application of thermoeconomic analysis in this specific area.[11,12]
3. *Industrial and thermal systems*: Thermoeconomics has been applied to industrial and thermal systems, with a focus on cost accounting, optimization, and diagnosis of these facilities.[4,13]
4. *Building thermal systems*: The use of thermoeconomics in building thermal systems is becoming increasingly important in promoting energy savings and reducing environmental impact.[14,15]
5. *Various systems and plants*: The literature presents applications of thermoeconomic analysis in a wide variety of systems and plants, reflecting its diverse scope.[16]

These classifications demonstrate the wide applicability of thermoeconomics in different types of facilities, ranging from energy systems to building thermal systems. It is relevant for addressing complex energy challenges in various domains.

On the other hand, a number of studies have been carried out on the use of waste heat and the consequent improvement in the energy efficiency of various industrial processes. Farhat et al. provided a comprehensive review of waste heat recovery methods and proposed a classification of waste heat recovery systems into 3 categories based on waste gas temperature, equipment used, and recovery methods.[17] In 2022, the European Commission released the CORDIS results package on waste heat recovery.[18] This resource discusses clean technologies developed in Horizon 2020-funded projects that aim to improve energy efficiency in process industries by utilizing waste heat. The focus is on reducing the impact of energy-intensive industrial processes through innovative solutions. Jouhara et al. investigated waste heat recovery methods in the steel and iron, food, and ceramics industries. They concluded that heat recovery provides valuable energy sources and reduces energy consumption.[19] Oyedepo and Fakeye reviewed the importance of waste heat recovery technologies in achieving sustainable energy development in their study.[20] In 2021, Oyedepo and Fakeye reviewed waste heat recovery technologies as a means of achieving sustainable energy development.[20] The article explores the significance of utilizing waste heat for sustainable energy practices, emphasizing its role in improving energy efficiency. In 2022, Xiao et al.[21] explored a control method for waste heat utilization systems based on low-quality waste heat recovery. The article discusses the challenges of recovering low-quality waste heat effectively and the potential for promoting energy conservation and efficient use through innovative technologies. In a related study, Haddad et al. examined the efficiency of low and medium waste heat recovery solutions, with a particular focus on Rankine and complex cycles.[22] This research provides insights into the practical applications of waste heat recovery cycles and presents examples to illustrate their effectiveness in increasing industrial efficiency.

Research has been conducted on analyzing the thermoeconomics of industrial processes to increase the efficiency of waste heat utilization. For instance, the study titled “Thermoeconomic and Environmental Feasibility of Waste Heat Recovery of a Data Center Using Air Source Heat Pump”[23] examines the feasibility of recovering waste heat from a data center using an air source heat pump. The paper analyzes the economic and environmental aspects of utilizing waste heat in this context. In the article, "Thermoeconomic analysis of a new waste heat recovery system for large marine diesel engine and comparison with two other configurations,"[24] three waste heat recovery system configurations are proposed for the successful recovery of waste heat sources in diesel engines. The study conducts a thermoeconomic analysis to compare the different configurations and evaluate their efficiency in recovering waste heat. The article titled "Thermoeconomic analysis of a waste heat recovery system with fluctuating flue gas scenario"[25] examines the performance and economic viability of a waste heat recovery system that comprises a fin tube heat exchanger and an organic Rankine cycle system under fluctuating flue gas scenarios. The study conducts a thermoeconomic analysis to evaluate the system's efficiency and economic feasibility.

In the context of these lines of research, our article examines for the first time the applications and importance of thermoeconomics in the analysis and optimization of integrated waste energy recovery systems (IWERSs). IWERS is a system used in grocery stores to take advantage of the residual heat generated in bread ovens. This system, described in detail in Fernández,[26] uses the thermal energy of steam to heat domestic hot water (DHW). The aim is to provide an objective evaluation of this system for the utilization of the residual heat of the steam generated in the bread ovens of commercial establishments.

The IWERS system was designed to utilize waste heat from bakery ovens in commercial establishments, thereby reducing energy consumption and mitigating the issue of global warming. The recovery of waste heat from industrial and commercial processes enhances energy efficiency and diminishes greenhouse gas emissions,[17] aiding the transition towards a decarbonized economic model.[20] Furthermore, IWERS systems can help companies reduce their energy expenditure, making them more competitive and sustainable in the long term. The system reduces the environmental impact of industrial and commercial processes by decreasing the demand for primary energy sources.[26] The reduction in energy and water consumption achieved with the use of IWERS contributes to the global effort to combat climate change. The research aims to address the existing gap by conducting a thermoeconomic analysis that evaluates the actual energy efficiency of the system's components and the system as a whole. This will enhance the system's efficiency, minimize its economic impact, and improve its environmental performance. The findings of this study will contribute to the implementation and utilization of the system. In the context of the global consensus on building a clean, low-carbon, and efficient energy system and accelerating the transformation of the energy structure, developing and utilizing energy efficiently and cleanly is a top priority.[27]

2 | METHODOLOGY

Figure 1 illustrates the components of IWERS that will undergo thermodynamic analysis, including their respective flows of matter, energy, and work.

IWERS is designed to improve energy efficiency in the production of hot water in businesses with bakery ovens. The system consists of installing a 300-L hot water tank to take advantage of the heat released by the ovens. This way, the two bread ovens that a medium-sized supermarket usually has[17] use water for fermenting bread dough. The steam generated by the bread dough that is not absorbed is eliminated by mixing it with tap water in the steam condenser of each oven. The condensed steam is then discharged through the commercial sewerage network. The residual heat of this steam is used to heat the water stored in the hot water tank through a heat exchanger. A wet rotor water circulation pump is utilized to ensure proper water circulation between the steam condensers and the heat exchanger. Additionally, if necessary, hot water from three 50-L electric thermoses located in the bakery, butchery, and fishmongers' sections, supplements the heat supply required to reach 60°C at the water outlet of the hot water tank. The operation of these thermoses is minimized using temperature control units in the tank. Only the necessary thermos flasks operate to supplement the thermal energy used in the tank and provide the required amount of hot water. Centralized differential temperature control circuits are placed between each steam condenser and the hot water tank. The controllers are equipped with two thermal sensors: one to measure the temperature of the steam condenser and the other to measure the temperature of the hot water tank. When the temperature of the steam condenser is only 2°C higher than that of the tank (this temperature difference is adjustable), a solenoid valve in the corresponding steam condenser closes, stopping the flow of water through the steam condenser. When the two solenoid valves are closed, the wet rotor recirculation pump is also shut down to ensure pump safety and reduce power consumption. The system flows, as shown in Figure 1, are as follows:

Point 1: Inlet of tap water to electric water heaters.

Point 2A: Outlet of hot water from electric water heaters.

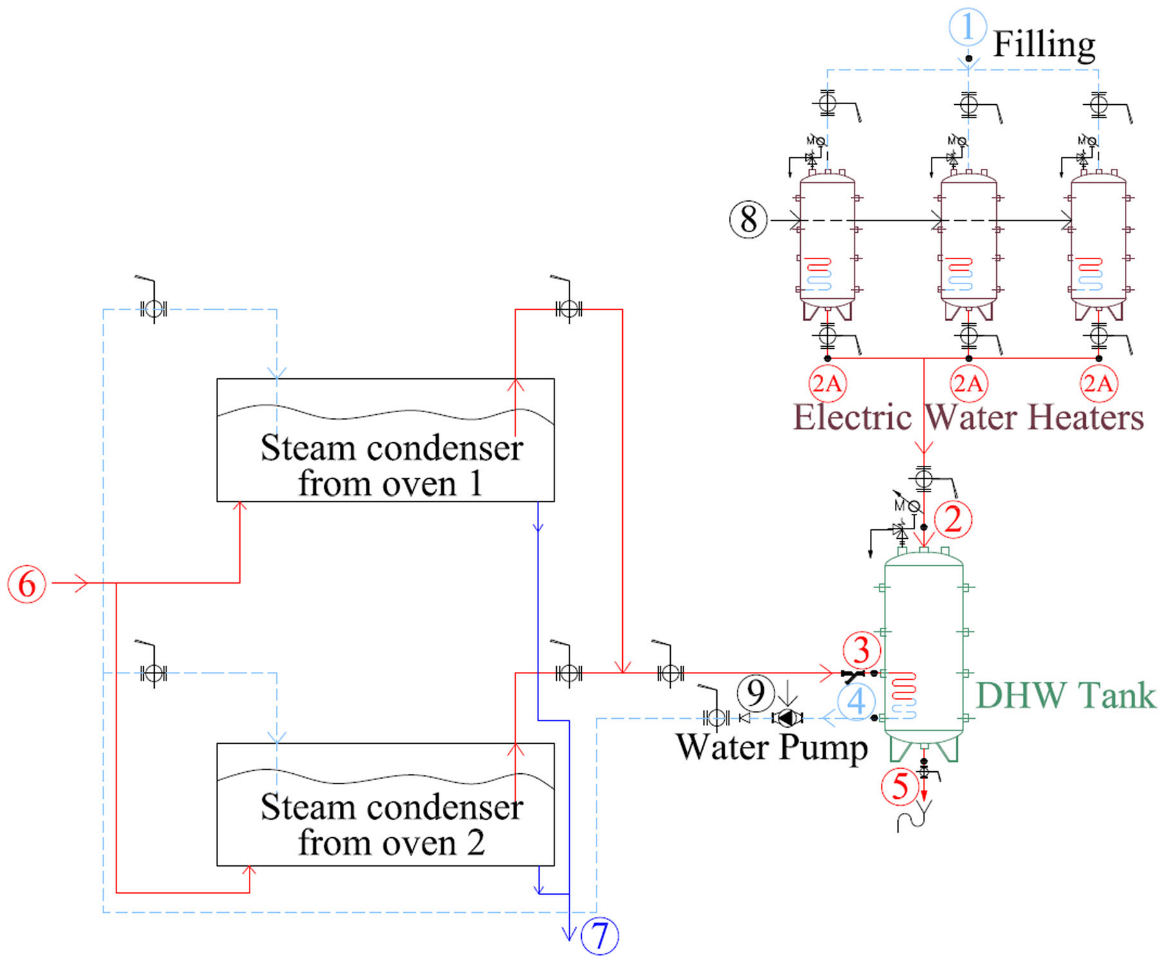

FIGURE 1 Components of IWERS and flows of matter, energy, and work. DHW, domestic hot water; IWERS, integrated waste energy recovery system.

Point 2: Inlet of water to DHW tank.

Point 3: Incoming hot water to the existing heat exchanger in the DHW tank (from steam condensers of ovens).

Point 4: Outgoing water from DHW tank used to condense steam in the steam condensers of the ovens (before entering the water pump).

Point 5: Hot water outlet from the DHW tank to supply hot water to the different services in the supermarket.

Point 6: Steam from the bread ovens.

Point 7: Water discharged to the supermarket's sewage system.

Point 8: Electric power supplied to the electric water heaters.

Point 9: Water from the DHW tank used in the condensation of steam within the steam condensers (after passing through the water pump).

Graph theory and linear algebra provide the necessary elements. Thus, an algebraic representation of the system structure is achieved through the incidence matrix, a vector representation of the matter and energy flows, and the execution of balances through matrix algebra. This way, the formal formulation of the problem is simplified, and the calculations can be repeated, as is usually required in systems analysis and synthesis tasks. To develop the thermoeconomic analysis in a progressive way, a system must be considered at the maximum level of aggregation, that is, in the form of a single unit or "black box." Figure 2 shows the IWERS under these conditions. All values of the thermoeconomic route were obtained according to the theoretical developments of the research,[28–32] as detailed below.

2.1 | Incident matrix

The incident matrix $A_{m \times n}$ represents the energetic connections of the system with its environment. Connections may involve flows of matter, heat, or exchange of work. The incidence matrix will have all its elements

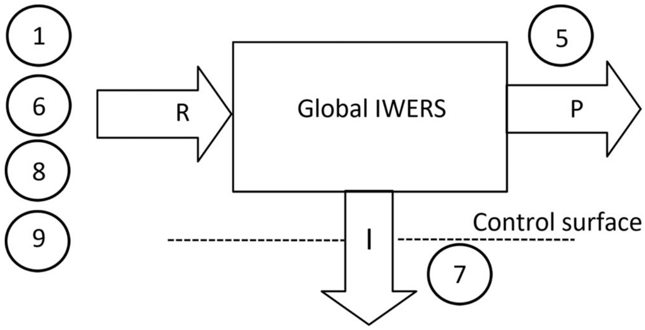

FIGURE 2 Global IWERS flows. IWERS, integrated waste energy recovery system.

null, except those related to currents between the system and its environment, which will be +1 or −1, depending on whether they enter or leave the system. Where m is the equipment and n are the fluxes or currents.

2.2 | Exergy vector

The exergy vector corresponds to a matrix $B_{1\times n}$. The components of the matrix will be the exergy values per unit of time in each of the teams.

2.3 | Exergy per unit of time or exergetic power of each piece of equipment

The mechanical work is pure exergy and therefore, if it exists, it will appear as $\dot{W}_n$. The heat flow would have to be multiplied by $(1 - T_0)/T_i$.[28] Where T_i is the temperature at which the heat transfer occurs. $\dot{B}_n$ represents the exergy flow that, if it exists, is not due to the transfer of heat or work done.

2.4 | Diagnostic vector

The diagnostic vector is calculated using the following equation[32]:

$$B_{d(1\times n)} = A_{(m\times n)} \cdot B_{(1\times n)}. \quad (1)$$

It represents the exergy that is destroyed in the equipment that makes up the system.

2.5 | Total exergy destruction

According to the general exergy equation,[28] the following exergetic balance was obtained:

$$\sum \dot{B}_{in} = \sum \dot{B}_{out} + \dot{B}_d + \dot{B}_L. \quad (2)$$

The input and output exergy values include both the exergy associated with the energy and material transfers in each element of the system. $\dot{B}_L$ represents lost exergy and $\dot{B}_d$ the total exergy destroyed, or also the total thermodynamic savings theoretically possible. Since exergy is an extensive property, the destruction in the system is the sum of the exergy destroyed in each of the devices.[32] This is,

$$\dot{B}_d = \sum_{i=1}^{i=m} \dot{B}_{d,i}. \quad (3)$$

Each element $\dot{B}_{d,i}$ of the diagnostic vector B_d represents the exergy destroyed in generic equipment i, therefore, the maximum energy saving theoretically possible in it.

2.6 | Exergy destruction rate

The comparison between $\dot{B}_{d,i}$ and the total exergy destruction gives an idea of the relative weight of each team in the exergy destruction or the total irreversibility of the system, through the exergy destruction rate d_i, defined as[32]

$$d_i = \frac{\dot{B}_{d,i}}{\dot{B}_d}. \quad (4)$$

This rate is typically expressed as a percentage by multiplying it by 100.

The analysis of the installation can be done with as much detail as desired, down to each piece of equipment, or even breaking down some pieces of equipment into several elements. The level of aggregation decreases, and the incidence matrix becomes more complicated. If we do the reverse, grouping certain elements into subsets of the system, the level of aggregation is increased, and the incidence matrix is simplified. In each specific case, we used a sufficiently low level of aggregation to achieve the objectives of the analysis with the least possible complexity.

The first part of the methodology was based exclusively on thermodynamics without introducing economic considerations, such as what resources are consumed, what products are used, or what waste is generated in the system. The evaluation of the quality of the system and its components was based exclusively on their greater or lesser thermodynamic perfection. For the development of thermoeconomic analysis, it was necessary to resort to the application of economic value concepts and judgments. First, it was necessary to know the economic or productive structure of the IWERS. To do this, it is necessary to know if the flows are a resource consumed by a team or a product generated by a team. According to the economic or productive structure of the system, the incoming or outgoing flows in each of the pieces of equipment that make it up have been classified as resources, products, and wastes or losses. The product (*P*) of a piece of equipment represents the desired useful effect it provides, according to its purpose. The resource (*R*) represents what is consumed to produce the product. But equipment can also have outgoing flows into the environment that have the character of waste or loss (with or without material flow), that is, without any useful effect (useless outputs); their set is known as the residue (*I*) of the team. This way, all equipment can be represented synthetically, according to Figure 2.

R, P, I are expressed in terms of exergy flows, as the sum of incoming flows classified as resources, products, or wastes minus the sum of outgoing flows of the same class.[32] That is to say:

$$\dot{R} = \sum \dot{B}_R^{+} - \sum \dot{B}_R^{-}, \tag{5}$$

$$\dot{P} = \sum \dot{B}_P^{-} - \sum \dot{B}_P^{+}, \tag{6}$$

$$\dot{I} = \sum \dot{B}_I . \tag{7}$$

2.7 | Exergetic or rational performance of the IWERS

The exergetic performance is defined as the ratio between the exergy of the products obtained and that of the resources consumed. It is calculated according to the following equation[32]:

$$z = \frac{\dot{P}}{\dot{R}}. \tag{8}$$

The unitary exergetic consumption of the IWERS and of each component is the inverse of the exergetic performance.[32] Therefore, it is calculated as

$$k = \frac{\dot{R}}{\dot{P}}. \tag{9}$$

2.8 | Exergetic cost

The exergy cost of an exergetic flown is defined as the exergy required to obtain that flow. It is depicted as B_n^*. The exergetic cost is an internal cost of the system, which depends on the exergy to be produced and the specific technology used and varies from case to case. It is necessary to point out that in a system, the energy consumed to produce an input to the system is not only generally unknown but also depends on the process followed and is something foreign to the system. It is, therefore, an exergetic external cost that should not be included in the analysis because it does not affect the system. Therefore, the inputs to the system are assigned exergetic costs equal to their exergy: $B_{inlet}^* = \dot{B}_{inlet}$.[32] The condition of nullity of the exergetic cost of the waste must be extended to all its components. Therefore, $B_I^* = 0$.[32] The following exergetic cost balance is also verified: $R^* = P^*$.[32]

It is important to note that when a resource enters the system from the environment (crossing the system's control surface), its exergetic cost is equal to its exergetic flow.[32] The exergy required to produce it is an external cost that does not affect the system being studied. Therefore, in this case, it is true that: $R^* = \dot{R}$. When carrying out the balance of exergetic cost, it is always true that the exergetic cost of incoming flows must be equal to that of the outgoing ones.[32]

$$\sum B_P^{*+} = \sum B_P^{*-}. \tag{10}$$

The exergetic cost vector denoted as $B_{(n\times1)}^*$ is defined as follows[32]:

$$A_{(m\times n)} \cdot B_{(n\times1)}^* = 0_{(m\times n)}. \tag{11}$$

2.9 | The unit exergy cost of each flow

The unit exergy cost of a current *n* is defined as the exergy required to obtain one unit of exergy from it. This is calculated using the following equation[32]:

$$\kappa_n^* = \frac{B_n^*}{\dot{B}_n}. \tag{12}$$

The expressions are calculated according to the equations[32]

$$R^* = \sum B_R^{*+} - \sum B_R^{*-}, \tag{13}$$

$$P^* = \sum B_P^{*-} - \sum B_P^{*+}, \tag{14}$$

$$I^* = \sum B_I^*. \tag{15}$$

This unit cost includes the effect of the thermodynamic perfection of the process and the economic criteria used to determine exergetic costs. The thermodynamic perfection of the process increases as the unit cost decreases. It is important to note that when a team produces multiple products (n), the unit exergetic costs assigned to each product output of that team are equal.[32]

$$\kappa_n^* = \frac{B^*_{procduct\ 1}}{\dot{B}_{product\ 1}} = \frac{B^*_{procduct\ 2}}{\dot{B}_{product\ 2}} = \cdots = \frac{B^*_{procduct\ n}}{\dot{B}_{product\ n}}. \quad (16)$$

This is because the exergetic cost is distributed in proportion to the exergies of the outputs, which represent their respective useful energy flows.

The calculations were based on actual operating and electrical consumption data collected over a 1-year period for each component. The IWERS analyzed was situated in a supermarket in northern Spain with two ovens, which experiences a temperate climate with warm winters and cool summers.

2.10 | Exergy associated with the *i*th material stream

The specific exergy related to the ith material stream was computed using the following equation[28]:

$$e_i = e_i^{PH} + e_i^{CH} + e_i^{KN} + e_i^{PT}. \quad (17)$$

Because they have little bearing, the terms related to kinetic (e_i^{KN}) and potential exergy (e_i^{PT}) are disregarded. Since the chemical makeup of the fluids involved in the various systems did not change, the chemical exergy (e_i^{CH}) was likewise disregarded. In this manner, the following equation was used to determine the exergy related to the ith material stream.[28]

$$\dot{E}x_i = \dot{E}x_i^{PH} = e_i \cdot \dot{m}_i = \dot{m}_{fluid} \cdot [(h_i - h_0) - T_0 \cdot (s_i - s_0)]. \quad (18)$$

The calculation of the exergy related to heat transfer was performed utilizing the subsequent equation.[28]

$$\dot{E}x_{Q,j} = \left(1 - \frac{T_0}{T_j}\right) \cdot \dot{Q}_j. \quad (19)$$

The ambient temperature (T_0) is the temperature of the system boundaries outside the device. The heat transfer rate at the boundary of the control volume, where the temperature is T_j, is denoted as $\dot{Q}_j$. This heat transfer rate can be calculated using Equation (20).[32,33] Where $\dot{m}$ is the mass flow rate, c is the specific heat, and ΔT is the temperature variation.

$$\dot{Q}_j = \dot{m} \cdot c \cdot \Delta T. \quad (20)$$

Montes et al. noted that thermoeconomics is known for its comprehensive approach that considers both thermodynamic and economic aspects.[32] This approach enables efficient energy management by evaluating not only energy consumption but also the associated costs. Furthermore, it provides an objective basis for identifying inefficiencies in energy processes, allowing for their correction and overall efficiency improvement. Thermoeconomics contributes to resource optimization and sustainability in energy processes by helping to understand the economic impact of energy inefficiencies and make informed decisions. Thus, thermoeconomics contributes to resource optimization and sustainability in energy processes by helping to understand the economic impact of energy inefficiencies and make informed decisions. This discipline also contributes to optimizing resources and promoting sustainability in energy processes. It helps understand the economic impact of energy inefficiencies and make informed decisions. Additionally, it evaluates renewable resources and promotes efficient energy supply. However, as Montes et al. detailed, thermoeconomics has limitations that must be taken into account when utilizing these technical disciplines. Assigning costs to products based on exergy destruction can be complex, as it requires in-depth knowledge of the processes and the ability to measure the exergy destroyed.[32]

3 | RESULTS

For each month of the year, Figure 3 shows the curve of total annual exergy destruction in IWERS calculated using the methodology specified. The annual exergy destruction was calculated by adding the exergy

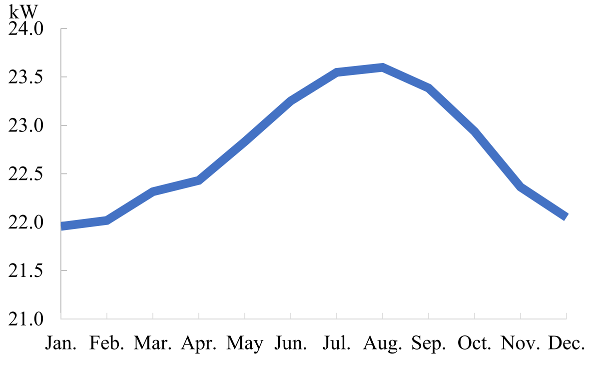

FIGURE 3 Annual exergy destruction in IWERS. IWERS, integrated waste energy recovery system.

destructions of each component of the IWERS, as detailed in Equations (2) and (3).

Exergy destruction is less during the coldest months of the year. Figure 4 shows the relative exergy destruction in the IWERS components.

During the coldest months of the year, the steam condenser had the highest exergy destruction rate, reaching close to 45% in each condenser. The electric boilers were the second least efficient equipment, with a destruction rate of 4% in each boiler during the warmer months. In contrast, the water pump was the most efficient equipment, with values similar to those obtained in the DHW tank. It was observed that during the summer months, the water pump, DHW tank, and steam condensers were more efficient compared to electric boilers. The steam condensers were the main source of exergy destruction, with values ranging between 84% and 85%. Therefore, improvements should be made in this area.

Figure 5 displays the exergetic or rational performance of the IWERS for each month of the year, with performance ranging from 20.7% to 24.6%. Higher values were observed during the colder months.

Table 1 shows the annual unitary exergetic consumption of the IWERS and its components. Both for the system as a whole and for all its elements, the highest values were obtained in the warm months. The only exception was the DHW tank, which obtained higher unitary exergetic consumption values during the colder months.

Table 2 shows the monthly unit exergetic cost for each flow. The highest values were the inlet flow to the tank from the steam condenser, followed by the inlet and outlet

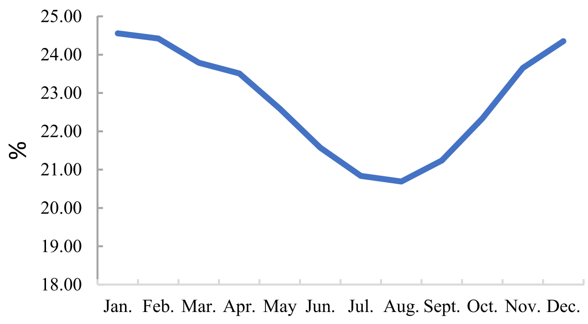

FIGURE 5 Exergetic performance of the integrated waste energy recovery system.

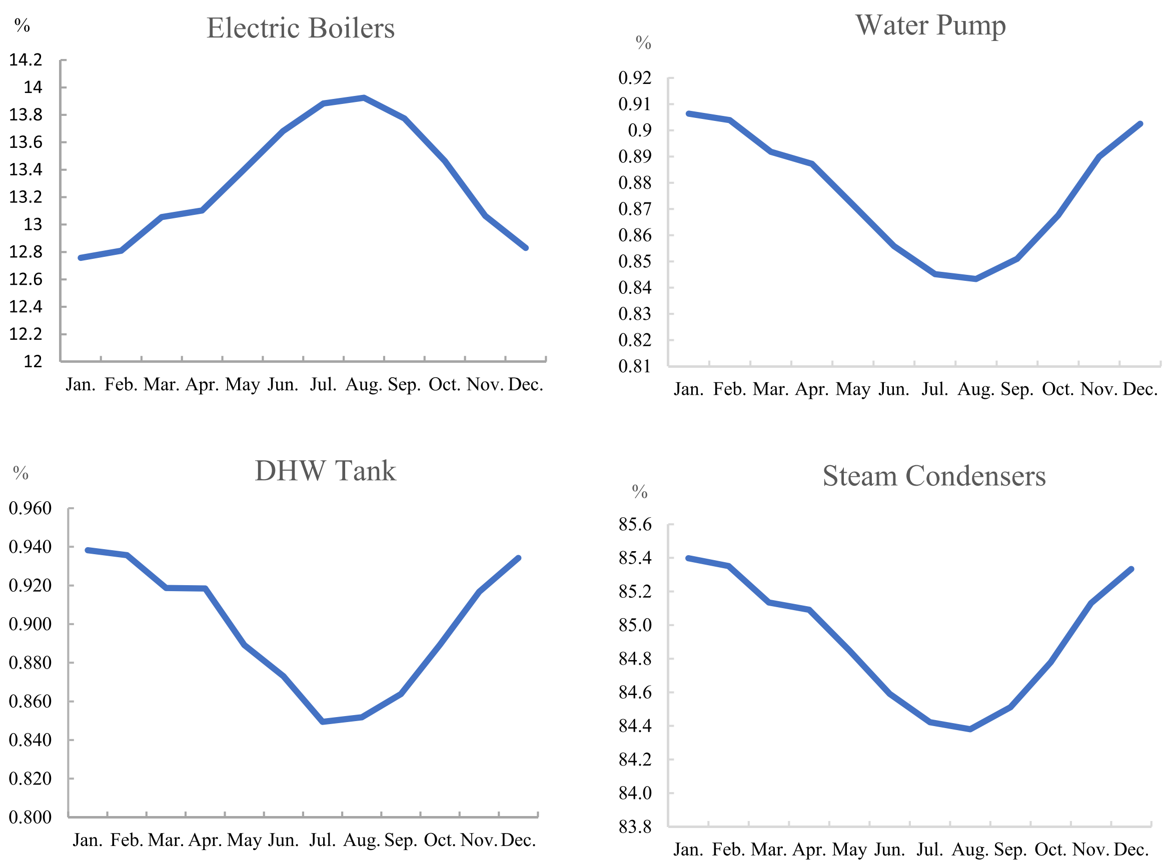

FIGURE 4 Relative exergy destruction in the IWERS components. DHW, domestic hot water; IWERS, integrated waste energy recovery system.

TABLE 1 Annual unitary exergetic consumption of the IWERS and its components.

	Electric boiler (3 units) (kW)	DHW tank (kW)	Water pump (kW)	Steam condenser (2 units) (kW)	IWERS (kW)
January	2.649	0.352	1.073	8.557	4.072
February	2.679	0.351	1.074	8.590	4.095
March	2.818	0.346	1.076	8.746	4.203
April	2.883	0.344	1.077	8.815	4.254
May	3.119	0.336	1.081	9.055	4.427
June	3.412	0.327	1.086	9.332	4.636
July	3.656	0.320	1.090	9.545	4.799
August	3.707	0.319	1.090	9.585	4.833
September	3.518	0.324	1.088	9.425	4.708
October	3.187	0.334	1.082	9.122	4.477
November	2.850	0.345	1.077	8.779	4.227
December	2.693	0.350	1.074	8.607	4.107

Abbreviations: DHW, domestic hot water; IWERS, integrated waste energy recovery system.

TABLE 2 Monthly unit exergetic cost for each flow.

	B_1^* (€/h)	B_2^* (€/h)	B_3^* (€/h)	B_4^* (€/h)	B_{4A}^* (€/h)	B_5^* (€/h)	B_6^* (€/h)	B_7^* (€/h)	B_8^* (€/h)	B_9^* (€/h)
January	0	4.50	65.38	39.37	39.57	30.51	25.81	0	4.50	0.20
February	0	4.50	65.33	39.37	39.57	30.46	25.76	0	4.50	0.20
March	0	4.50	65.19	39.43	39.63	30.26	25.56	0	4.50	0.20
April	0	4.50	65.14	39.47	39.67	30.17	25.47	0	4.50	0.20
May	0	4.50	64.99	39.61	39.81	29.88	25.18	0	4.50	0.20
June	0	4.50	64.89	39.82	40.02	29.57	24.87	0	4.50	0.20
July	0	4.50	64.88	40.03	40.23	29.35	24.65	0	4.50	0.20
August	0	4.50	64.86	40.06	40.26	29.30	24.60	0	4.50	0.20
September	0	4.50	64.88	39.91	40.11	29.47	24.77	0	4.50	0.20
October	0	4.50	64.97	39.67	39.87	29.80	25.10	0	4.50	0.20
November	0	4.50	65.16	39.45	39.65	30.21	25.51	0	4.50	0.20
December	0	4.50	65.31	39.37	39.57	30.44	25.74	0	4.50	0.20

flows of the water pump. These values were higher in the cold months in the case of the inlet flow to the tank and lower in the case of the flows passing through the water pump. Additionally, it was noted that the exergetic cost per unit of product (flow 6) increases by up to 4.2% during the summer. Highlighting the importance of considering seasonal variations in energy consumption and costs, optimizing the operation of the IWERS to consider these variations could result in significant economic savings.

These results also have implications for sustainability and environmental impact. Improving the exergy performance of the IWERS could reduce the overall environmental impact of the system, making it more sustainable and environmentally friendly.

4 | CONCLUSIONS

The results offer valuable insights into exergy destruction and IWERS performance, with significant implications for energy efficiency, economic savings, and sustainability.

Improving system efficiency could lead to substantial benefits in energy savings, economic savings, and environmental impact for all commercial and industrial establishments that use bakery ovens.

Exergy destruction in IWERS is directly proportional to the ambient temperature.

The steam condenser is the least efficient equipment in the IWERS system, as it is responsible for almost half of the exergy destruction in the system.

Exergetic cost in IWERs slightly decreases with ambient temperature, decreasing by less than 1%. This effect is observed in summer when temperatures are higher.

The study has significant practical implications for supermarkets and factories that manufacture frozen dough and bakery products using ovens equipped with steam condensers.

Incorporating equipment upstream of the process results in an increase in the exergy cost of the output due to the destruction of exergy in the equipment. This phenomenon is referred to as the internalization of irreversibility and external exergetic costs, also known as the substitution theorem.

Thermoeconomic diagnostic procedures in the literature consider specific resource consumption of components as crucial for interpreting the effects of dysfunction and tracing the sources of anomalies. However, the results indicate that interactions between components can cause changes in specific consumption and obscure the root cause of the dysfunction. This presents a major challenge for the effective application of these approaches.

As a limitation of the study and a future line of research, it is worth noting the possibility of extending the study to businesses located in different climatic zones to analyze the efficiency of the system in relation to climatic factors and operational scenarios. This would provide additional data to improve the system's applicability and its components.

NOMENCLATURE

e	specific exergy (kJ kg^{-1})
Ex	exergy (kJ)
$\dot{Ex}$	exergy flow rate (kW)
h	specific enthalpy (kJ kg^{-1})
I	waste
m	mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
P	product
Q	heat transfer (kJ)
$\dot{Q}$	heat transfer flow rate (kW)
R	resource
s	specific entropy (kJ K^{-1} kg^{-1})
S	entropy (kJ K^{-1})
T	temperature (K or °C)
T_0	average monthly/yearly temperature (K or °C)

GREEK LETTERS

Σ	sum

SUBSCRIPTS

d	destroyed
ex	exergetic
i	ith material stream
in	input
j	jth instant
L	lost
out	output
0	ambient or surrounding value

SUPERSCRIPTS

CH	chemical
KN	kinetic
PH	physical
PT	potential
+	incoming flows
−	outgoing flows
.	flow rate
*	exergetic cost

UNITS

°C	degrees Celsius

CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

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