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Universidad Tecnológica Nacional, Argentina

*CORRESPONDENCE
O. M. Oyewola,
oooyewola001@gmail.com,
ooyewola@alaska.edu

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Energetic, exergetic, and exergoeconomic analyses of beer wort production processes

O. S. Jemigbeyi[1], T. A. O. Salau[1] and O. M. Oyewola[2]*

[1]Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria, [2]Department of Mechanical Engineering, University of Alaska Fairbanks, Fairbanks, AK, United States

Energy efficiency strategies in industrial breweries examine the inefficiency of thermal systems from a thermodynamic perspective. However, understanding the costs of inefficiencies in systems, including non-thermodynamic costs, requires exergoeconomics. This study examined wort production in a standard Tier-1 brewery from the tripod of energy, exergy, and exergoeconomics analyses to assess the performance of brewing sections and to pinpoint components that contributed the most to exergy destruction and product cost rate. The energy analyses for the production system showed that the total specific energy for processing 10.05 tons of brew grains to 346.98 hL high-gravity wort was (86 ± 1) MJ/hL at an operational energy efficiency of 30.35%. The exergetic analyses showed that the cumulative exergetic destruction was 3.2737 MW, with the brewhouse section contributing 89.25% of the system's inefficiencies. Also, the analyses showed that the wort kettle (42.7911%), mash tun (10.8086%), preheater (10.0683%), whirlpool (8.3522%), and adjunct kettle (6.2705%) are the top five components with the highest rates of cumulative exergy destruction. The exergoeconomic analyses revealed that the cost rate of processing chilled wort was estimated to be 0.0681 USD/s per overall exergetic efficiency of 6.61%. The five most significant components are the wort kettle (53.70%), whirlpool (16.42%), mash filter (10.44%), mash tun (6.875%), and adjunct kettle (3.31%) based on the relative total cost increases for the production processes. Additionally, wet steam throttling resulted in a 2.51% increase in exergetic efficiency, a 1.60% drop in exergetic destruction rate, and a decrease in cost rates to 0.0675 USD/s.

KEYWORDS

exergoeconomics, exergy, energy, industrial brewing, mash, wort

1 Introduction

Brewers operate in a highly competitive business environment, aiming to reduce production costs, maintain beer quality, and minimize the environmental impact of by-products. The brewing process is energy-intensive, particularly in the brewhouse section (Scheller et al., 2008; Willaert and Baron, 2005). There have been various models and recommendations for optimizing energy usage in brewing processes (Dumbliouskaite et al., 2010; Tokos et al., 2010; Scheller et al., 2008; Mignon and Hermia, 1993). Bai et al. (2011) proposed an energy consumption model for brewing processes based on production data. They evaluated energy consumption patterns employing three modeling analyses and found out that results from their simulation analyzed and forecasted energy consumption for beer brewing processes effectively. Fadare et al. (2010) found out that mash conversion and wort boiling processes accounted for the majority of the total inefficiency in a malt drink plant

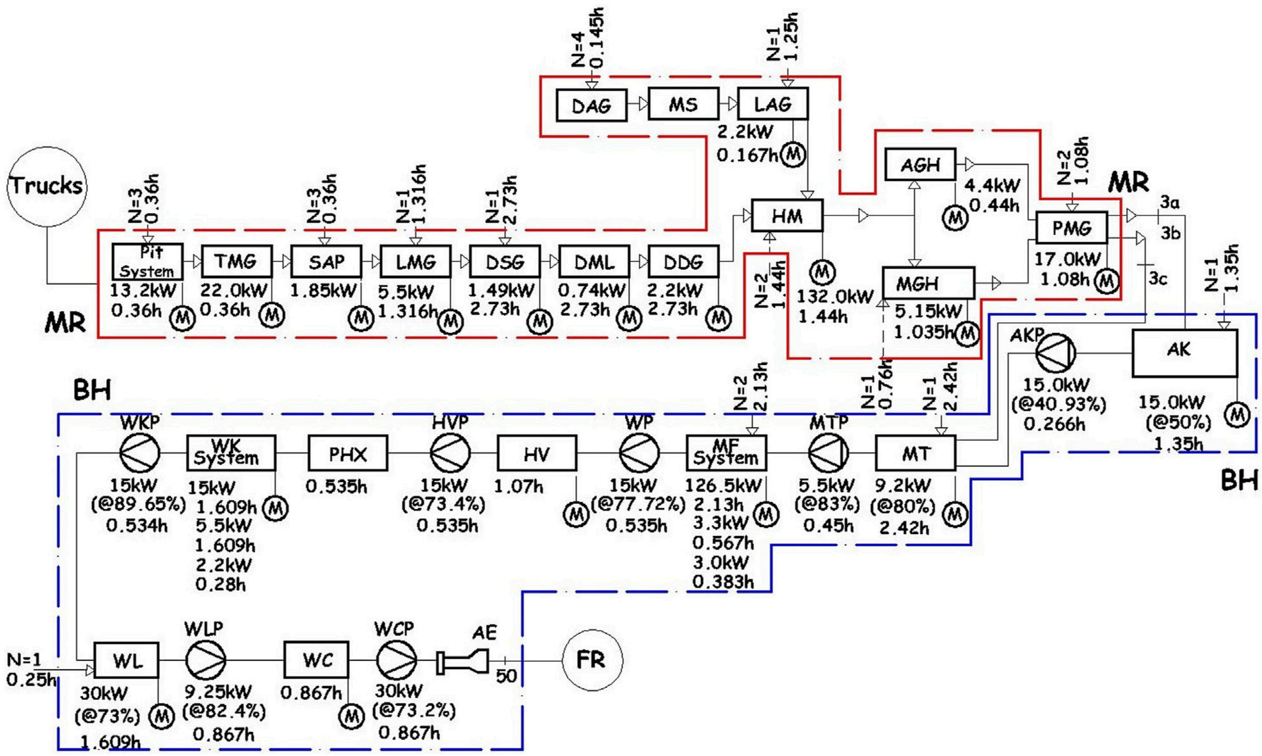

FIGURE 1
Process chart for wort production depicting components' operational power and duration and human energy expenditure figures. MR = Milling Room {TMG = Transportation of malted barley grains to silos; SAP = Silo aspiration system; LMG = Loading of malted barley grains; DSG = Destoner; DML = Demetallizer; DDG = Deduster; HM = Hammer miller; MGH = Malt grist holder; DAG = Discharge of adjunct grains; MS = Maize Store; LAG = Loading of adjunct grist; AGH = Adjunct grist holder; PMG = Premasher}. BH = Brewhouse {AK = Adjunct Kettle; AKP = Adjunct Kettle Pump; MT = Mash Tun; MTP = Mash Tun Pump; MF = Mash Filter; WP = Wort Pump; HV = Holding Vessel; HVP = Holding Vessel Pump; PHX = Preheater; WK = Wort Kettle; WKP = Wort Kettle Pump; WL = Whirlpool; WLP = Whirlpool Pump; WC = Wort Cooler; WCP = Wort Cooler Pump; AE = Aerator}. N = Number of assigned person (s). FR = Fermentation Room. MR Section: BH Section.

and proposed process heat integration for steam-loaded components to improve energy efficiency. Hence, reducing energy intensity in brewhouse mashing and wort boiling processes could allow for the design of heat supply components at a lower capacity.

In Slawitsch et al. (2014), the effects of brewing parameter changes on the energy demand for main brewhouse processes for real and hypothetic sites were studied using a developed brewing model. A 710,000 hL capacity hypothetic site showed possible energy intensity values of 4.84 and 7.62 MJ/hL for mashing and wort boiling processes, respectively, and they found that new temperature profiles in these operations could support the integration of low-temperature process heating in a brewhouse. Importantly, considering the increasing emphasis on carbon footprint and sustainability in manufacturing and production processes, there remains a continuous need to improve energy utilization per hectoliter of brewed products to minimize production costs.

Energy costs make up about 38 percent of the total beer production cost (Galitsky et al., 2003), and the beer industry, like other manufacturing sectors, cannot predict earnings due to the uncertainties surrounding energy prices in today's market. Exergoeconomics is an approach that optimizes energy conversion systems in terms of exergy destruction and process cost formation. It helps to pinpoint variables that increase the total cost rates of equipment based on exergy destruction, external irreversibility, equipment capital recovery, and operations and maintenance (O&M) costs. Exergy costing assigns costs to a process stream based on its exergetic value, which is the rational basis for determining costs associated with a system's internal and external irreversibilities (Bejan et al., 1996; Morosuk et al., 2012). However, cost is the amount of input resources required to produce a product. It is an emergent property that arises from the interplay among components in the course of productive operations (Valero and Torres, 2009). And unlike thermodynamic properties, costs are not inherent to a component or a product. Thus, to evaluate cost accurately, a standardized rule based on physical properties is necessary.

In the exergoeconomics study, methodologies such as Engineering Functional Analysis (EFA), Exergetic Cost Method (EXCEM), Average Costing Method (AVCO), Last-In, First-Out method (LIFO), and Specific Exergy Costing (SPECO) have been developed. These methodologies are classified into two major approaches: the Lagrangian-based approach and the exergoeconomic accounting-based approach. The Lagrangian-based approach optimizes an entire system and evaluates marginal cost using partial derivatives (Frangopoulos, 1992). In the accounting-based methodology, the exergoeconomic evaluation is primarily to cost product streams, with the cost of input streams from upstream components assumed or known, and the evaluation of components based on established variables (Erlach et al., 2001).

Although exergoeconomics has been a field of study since 1984 (Tsatsaronis, 2007), there are limited reports on its application in food processing systems. Most of the existing studies have focused on food drying operations (Hepbasli et al., 2010; Gungor et al., 2012; Li et al., 2020; Tinoco-Caicedo et al., 2020; Erbay and Kocay, 2012). Interestingly, no study has explored the potential of brewing operations in open literature. Expectedly, exergoeconomic studies of brewing operations would aid brewers to accurately evaluate and minimize their costs, ensuring more efficient and sustainable processes. Moreover, they can stay ahead of the competition by producing high-quality beer at cost-effective prices. Hence, this study examined the exergetic and exergoeconomic performances of wort production at a large-scale industrial brewery in Nigeria, using the Specific Exergy Costing (SPECO) approach. The focus was to quantify the energy consumption, exergetic destruction rate, functional efficiency, improvement potentials, and cost of processed streams for wort production. Also, components with the highest relevance concerning exergy destruction and cost rates were identified. Expectedly, the research findings will be useful to stakeholders in the brewing sector and academia in optimizing wort production for better sustainability.

2 Materials and method

2.1 Brewery description

The facility under study is a Tier-1 brewery that produces over 1.8 million hectoliters annually. It offers premium alcoholic and non-alcoholic malt drinks, with remarkable corporate social responsibilities. To generate process heat, the brewery used three sequenced boiler sets that produced 15,000 kg of steam per hour. Electricity was supplied by the national grid via an 800 kVA transformer and five onsite power generating sets, including one 800 kVA, three 1,000 kVA, and one 1,250 kVA.

2.2 Operation and process descriptions of wort production sections

Wort is a primary product resulting from the conversion of brewing grains, and it is an aqueous solution containing fermentable sugars (such as glucose, fructose, sucrose, maltose, and maltotriose), as well as assimilable nitrogen, oxygen, biotin (a vitamin), calcium, and trace elements (Fox and Bettehausen, 2023). It is processed from starch-rich cereals. Approximately 70%–75% of the sugars in wort are fermentable, while the remaining composition consists of unfermentable longer-chain saccharides and polymers (Mua and Jackson, 1995). Wort plays a central role in beer production and is responsible for the high thermal load associated with brewing operations.

The wort brewing process in craft and large breweries is divided into two primary sections: the grains handling and milling room (also called Milling Room, MR) and the brewhouse (BH). The grains handling and milling room involves handling and milling malted barley and adjunct (maize) grains to produce grist, which is then utilized in the brewhouse. Figure 1 provides a combined schematic illustration of the grains handling and milling room (MR) and brewhouse (BH) sections. The grains handling and milling room encompasses various processes including: Transportation of Malted Grains into silos (TMG), Discharge of Adjunct maize Grains into storage (DAG), Silo Aspiration (SAP), Loading of Malted Grains (LMG), Loading of Adjunct maize Grains (LAG), Destoning (DSG), Demetallizing (DML), Dedusting (DDG), Hammer Milling (HM), Malt Grist Holding (MGH), Adjunct maize Grist Holding (AGH), and Premashing (PMG). The premasher handles three processes, as shown in Figure 1: premashing of adjunct maize into the adjunct kettle, Stream 3a; premashing of adjunct malt barley into the adjunct kettle, Stream 3b; and premashing of malted barley into the mash tun, Stream 3c.

The brewhouse, often referred to as the “kitchen,” is the section where saccharification and sparging of mash, cooking, clarification, and cooling of wort take place. The brewhouse comprises an Adjunct Kettle (AK), Mash Tuns (MT), Meura Filter 2001 (MF), Holding Vessel (HV), wort preheater (PHX), Wort Kettle (WK), Whirlpool (WL), Trub tank (TB), Wort Cooler (WC), Chilled Water Tank (CWT), Very Hot Water Tank (VHWT), Hot Water Tank (HWT), and seven different pumps (Adjunct Kettle Pump (AKP), Mash Tun Pump (MTP), Wort Pump (WP), Holding Vessel Pump (HVP), Wort Kettle Pump (WKP), Whirlpool Pump (WLP), and Wort Cooler Pump (WCP). The wort kettle is a thermal vessel responsible for three crucial processes in the brewhouse: the wort preboiling (WKPB), wort boiling (WKB), and wort stripping (WKS) to produce wort of desired physiochemical profiles.

2.3 General research framework

2.3.1 Data sources and gathering procedures

Data were collected by directly recording operating parameters for three types of energy input (electrical, human, and thermal) and the mean values of the recorded data (basic properties for brewing streams and components) over a 1-year brewing period were used for analyses. Technical specifications of components were obtained from equipment sheets or number plates. Where vendor quotations and past invoices of purchased brewing components were not available, historical data, cost estimation models, and online prices (from matche.com and czechminibreweries.com, Supplementary Table SA1) were used to estimate component costs.

The Purchase Equipment Costs (PECs) were generated and the popular power sizing model and cost index model were adopted for evaluating the PECs of components that were not directly available for year 2019. The cost index model was used for cost escalations for two different years based on the Chemical Engineering Plant Cost Index. CEPCI.

2.3.2 General assumptions

The energy and exergy aspects of all components and sections of the wort production line were evaluated based on the following general considerations: a) Steady-state conditions were assumed for all process streams and components; b) Potential, kinetic, and chemical interactions energy effects were not considered; c) Dead state temperature and pressure were set to 25°C and 1 bar, respectively; d) Brewing grains at the milling room's entry points were at dead state.

2.4 Formulation of energy effects for component processes

The energy inputs for the brewing processes were defined as follows.

2.4.1 Human energy

Energy expenditure in human is influenced by individual characteristics like age, gender, functional capacity, and anthropometrics. The Equation 1 employed for the evaluation of human energy expenditure in Dhanushkodi et al. (2016) was adopted:

$$E^h = 0.27 \times N \times t\,(\mathrm{MJ}) \quad (1)$$

N is the count of persons involved and t is the time required to complete an activity in hours.

2.4.2 Electrical energy

The electrical energy inputs for components were evaluated based on the rating of motors (P), duration of operation (t) for a batch process as defined by Equation 2

$$E^e = 3.6 \times \eta \times \mathrm{P} \times \mathrm{t}\ (\mathrm{MJ}) \quad (2)$$

Where motor efficiency, η = 80% as presented in Waheed et al. (2008).

2.4.3 Energy content of material streams

The available heat content E^q of a matter stream was defined with respect to dead state as defined by Equation 3

$$E^q = 0.001 \times m_i \times \Delta h.\,(\mathrm{MJ}) \quad (3)$$

Where, $\Delta h = C_P \times (T - T_o)$; m = mass of stream (kg); h = specific enthalpy of stream (kJ/kg); C_P = specific heat capacity of stream in kJ/kg.K; and T = temperature of stream.

The C_p value for food streams rises as the moisture content increases. It depends on the food's composition and can be determined from literature or predictive models. In this study, we evaluated C_p using the mass fractions and temperature-dependent functions of each component of a food stream, as presented in Singh and Heldman (2013), Equation 4:

$$C_p = \sum_i x_j C_{p,j} \quad (4)$$

Where x_j = mass fraction of constituent j and $C_{p,j}$ = specific heat of constituent j in stream i.

At the brewery studied, the brewing process involved using malted barley and adjunct maize to create the wort. The compositions of these ingredients matched the results from the brewery's laboratory. The compositions of the brewing grains and the models for specific heat and density evaluations are detailed in Supplementary Table SA2.

2.4.4 Formulation of energy efficiencies

The thermal efficiency of a production section ($\varnothing$) was defined by Equation 5a

$$\varnothing = \frac{\sum \dot{m}_{out}\Delta h_{out}}{\sum \dot{m}_{in}\Delta h_{in}} \quad (5a)$$

Where $\sum \dot{m}_{out}\Delta h_{out}$ and $\sum \dot{m}_{in}\Delta h_{in}$ are the summation of the heat content of a section's output and input matter streams, respectively.

The thermal efficiency of a component, φ_k, was defined by Equation 5b

$$\varphi_k = \frac{\sum \dot{m}_e \Delta h_e}{\sum \dot{m}_i \Delta h_i} \quad (5b)$$

Where $\dot{m}_e\Delta h_e$ and $\dot{m}_i\Delta h_i$ are the heat contents of a component's output and input streams respectively.

The overall energy efficiency of the wort system was computed based on Equation 5c

$$\eta = \frac{\sum \dot{m}_{out}\Delta h_{out}}{\sum \dot{m}_{in}\Delta h_{in} + \dot{W}_{cv}} \quad (5c)$$

Where $\dot{W}_{cv}$ is the total amount of electrical and human energy across the production system.

2.5 Propagation of uncertainties for energy inputs

As presented in Gertsbakh (2003), Equation 6 was adopted to evaluate uncertainties in energy values to aid data reproducibility and representativeness

$$\delta_A = \left\{ \left(\frac{dA}{dx} \times \delta x\right)^2 + \left(\frac{dA}{dy} \times \delta y\right)^2 + \left(\frac{dA}{dz} \times \delta z\right)^2 \right\}^{½} \quad (6)$$

2.6 Formulation of exergetic effects of material and energy streams

Mass and exergy balance rates for streams of a component k were evaluated as defined in Equations 7, 8, respectively:

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (7)$$

$$\dot{E}x_d = \sum \left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k + \dot{W}_{CV} + \sum_k \dot{m}_i ex_i - \sum_k \dot{m}_e ex_e \quad (8)$$

Regarding food streams, the specific physical exergetic effect is assessed using the equation for incompressible condensed substance.

The exergetic effect associated with energy streams for a component's process was defined by Equation 9

$$\dot{W}_{CV} = \dot{E}x^h + \dot{E}x^e \quad (9)$$

Both human and electrical energy inputs have physical exergetic effects equivalent to their energy values. For steam and hot water process streams, the specific physical exergetic effect was evaluated using the specific enthalpies and entropies of the streams' states as defined in Equation 10.

$$ex = (h - h_o) - T_o(s - s_o) \quad (10)$$

For food streams, the specific physical exergetic effect was estimated using the Equation 11, for incompressible condensed substance:

$$\mathrm{ex} = \mathrm{C_p}\left(\mathrm{T} - \mathrm{T_o}\right) - \mathrm{C_p T_o In}\left(\mathrm{T}/\mathrm{T_o}\right) + \vartheta\left(\mathrm{P} - \mathrm{P_o}\right) \tag{11}$$

The values of C_p and ϑ (= $^1/_\rho$) are temperature-dependent as shown in Supplementary Table SA2.

2.7 Exergetic performance models

To comprehensively capture irreversibility and improvement potential, four exergetic performance indicators were utilized, as relying solely on exergetic efficiency is inadequate.

a) Functional Exergetic Efficiency, FEE, φ_{II}:The FEE was defined by Equation 12 (Tsatsaronis and Winhold, 1985):

$$\varphi_{II} = \frac{\sum \mathrm{Ex\ of\ desired\ product}}{\sum \mathrm{Ex\ of\ used\ fuel\ (resources)}} = \frac{\dot{\mathrm{E}}\mathrm{x}_{P,k}}{\dot{\mathrm{E}}\mathrm{x}_{F,k}} \tag{12}$$

Exergetic efficiency is a measure that assesses the effectiveness of exergetic inputs within a process or chain. It invariably presents a lower value than energetic efficiency due to the representation of deviation of the current food chain from ideality (Zisopoulos, 2016).

b) Exergy Destruction Rate, $\dot{\mathrm{E}}\mathrm{x}_d$: Genc et al. (2017) defined exergy destruction rate as shown in Equation 8, providing insights into the irreversibly lost work during a process in relation to a reference environmental condition.
c) Exergetic Improvement Potential, IP: The IP was defined by Equation 13 (Zisopoulos et al., 2015; Dogbe et al., 2017):

$$\mathrm{IP} = \left(1 - \varphi_{II}\right) \times \left(\dot{\mathrm{E}}\mathrm{x}_i - \dot{\mathrm{E}}\mathrm{x}_e\right) \tag{13}$$

The concept of Improvement Potential provides a means of assessing the potential for improvement in a process, with the understanding that the maximum improvement for a given process equates to its total exergy loss, limited by techno-economic constraints.

A component/system with a high IP indicates low efficient use of resources and great potential for improvement.

d) Exergetic sustainability index, SI: The SI was defined by Equation 14 (Dogbe et al. (2017); Zisopoulos et al. (2015)):

$$\mathrm{SI} = {}^{1}/\left(1 - \varphi_{II}\right) \tag{14}$$

The sustainability index signifies a superior efficiency for a process with a higher value and it is the reciprocal of exergetic destruction ratio, $\dot{y}_d$. Higher irreversibility results in a lower sustainability index, and *vice versa*.

2.8 Exergoeconomic parameters formulations

The exergoeconomic investigation of a system deploys the combined applications of exergetic and economics analyses to generate important data necessary for the cost-effective operation of system components by evaluating the costs of materials, energy streams, and destroyed exergy. Applicable economics formulations for main components were defined below.

2.8.1 Economics models for component costs

Due to the limited availability of vendor quotations and previous invoices for brewing components purchased from the brewery under investigation, this study has relied on historical data, cost estimation models, and online prices sourced from matche.com (2014), Czechminireweries.com (2024) to provide an approximate estimate of component costs. Careful consideration has been given to ensure that reasonable costs are employed in the calculation of Purchase Equipment Costs (PECs) as detailed in appendix Supplementary Table SA2. The power sizing equation (Equation 15) and the cost escalation model (Equation 16) were utilized to perform the estimation of PECs.

$$C_B = C_A \times \left(\frac{S_B}{S_A}\right)^a \tag{15}$$

Where, C_B = Capital cost of component with known capacity, S_B; C_A = Capital cost of component with known capacity, S_A; a = size exponent.

For cost escalation across different years (Towler and Sinnott, 2008),

$$C_{Year,B} = C_{Year,A} \times \left(\frac{CI_{Year,B}}{CI_{Year,A}}\right) \tag{16}$$

$C_{Year,A}$ a known cost of a component for a referenced Year A with its corresponding cost index for the year, $CI_{Year,A}$; $CI_{Year,B}$, a known cost index for a referenced year for a component cost to be estimated. The referenced year for this study was 2019.

2.8.2 Formulation of economics models for amortized cost rates of components, $\dot{Z}_k$

The amortized cost rates of components, $\dot{Z}_k$ was defined by Equation 17

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{17}$$

$\dot{Z}_k^{CI}$ = levelized Total Capital Investment, TCI, cost rate for a component, k

$\dot{Z}_k^{OM}$ = levelized Operations and Maintenance (O&M) cost rate for a component, k

In 2019, the brewery invested in a new brewhouse. In order to make well-informed economic decisions regarding the equipment, the annual equivalent capital cost is computed as the levelized or amortized cost over its service life. It is important to note that sunk costs are not considered relevant, but the equipment's value depreciates over time with a corresponding salvage value, as shown in Equation 18 (Chan, 2007).

$$Z^{CI}(i) = I\left(A/P, i, N\right) - S_N\left(A/F, i, N\right) \tag{18}$$

I = TCI for a component and $(A/P, i, N)$ is Capital Recovery Factor (CRF) and defined by Equation 19

TABLE 1 Exergy and exergoeconomics formulations for main components in wort production.

Premasher processes (Adjunct Maize Grist MG, Adjunct Malt Grist AM, Malt Grist MG)	
$\dot{Ex}_d$	$\dot{m}_i ex_i + \dot{w}_{cv} - \dot{m}_e ex_e$
φ_{II}	$\frac{\dot{m}_e ex_e}{\dot{m}_i ex_i + \dot{w}_{cv}}$
Cost rate	$c_i \dot{m}_i ex_i + c_{wcv} \dot{w}_{cv} + \dot{Z}_k + \dot{C}_h = c_e \dot{m}_e ex_e$
Adjunct Kettle (AK)	
$\dot{Ex}_d$	$\dot{m}_{3a} ex_{3a} + \dot{m}_{3b} ex_{3b} + \dot{m}_4 ex_4 + \dot{m}_5 ex_5 + \dot{w}_{AK} - (\dot{m}_9 ex_9 + \dot{m}_{10} ex_{10})$
φ_{II}	$\frac{\dot{m}_9 ex_9 + \dot{m}_{10} ex_{10}}{\dot{m}_{3a} ex_{3a} + \dot{m}_{3b} ex_{3b} + \dot{m}_4 ex_4 + \dot{m}_5 ex_5 + \dot{w}_{AK}}$
Cost rate	$c_{3a} \dot{m}_{3a} ex_{3a} + c_{3b} \dot{m}_{3b} ex_{3b} + c_4 \dot{m}_4 ex_4 + c_5 \dot{m}_5 ex_5 + c_{wAK} \dot{w}_{AK} + \dot{Z}_{Ak} + \dot{C}_{hAK} = (c_9 \dot{m}_9 ex_9 + c_{10} \dot{m}_{10} ex_{10})$
Auxiliary	$\dot{C}_{10} = (\dot{C}_6 / \dot{Ex}_6) \times \dot{Ex}_{10}$ F-Rule
Brewhouse pumps (AKP, MTP, WP, HVP,WKP, WLP, WCP)	
$\dot{Ex}_d$	$\dot{m}_i ex_i + \dot{w}_{cv} - \dot{m}_e ex_e$
φ_{II}	$\frac{\dot{m}_i (ex_e - ex_i)}{\dot{w}_{cv}}$
Cost rate	$c_i \dot{m}_i ex_i + c_{wcv} \dot{w}_{cv} + \dot{Z}_k + \dot{C}_{hK} = c_e \dot{m}_e ex_e$
Mash Tun (MT)	
$\dot{Ex}_d$	$\dot{m}_{11} ex_{11} + \dot{m}_6 ex_6 + \dot{m}_{13} ex_{13} + \dot{m}_{3c} ex_{3c} + \dot{m}_{12} ex_{12} + \dot{w}_{MT} - (\dot{m}_{19} ex_{19} + \dot{m}_{20} ex_{20})$
φ_{II}	$\frac{\dot{m}_{19} ex_{19} + \dot{m}_{20} ex_{20}}{\dot{m}_{11} ex_{11} + \dot{m}_6 ex_6 + \dot{m}_{13} ex_{13} + \dot{m}_{3c} ex_{3c} + \dot{m}_{12} ex_{12} + \dot{w}_{MT}}$
Cost rate	$c_{11} \dot{m}_{11} ex_{11} + c_6 \dot{m}_6 ex_6 + c_{13} \dot{m}_{13} ex_{13} + c_{3c} \dot{m}_{3c} ex_{3c} + c_{12} \dot{m}_{12} ex_{12} + c_{wMT} \dot{w}_{MT} + \dot{Z}_{MT} + \dot{C}_{hMT} = (c_{19} \dot{m}_{19} ex_{19} + c_{20} \dot{m}_{20} ex_{20})$
Auxiliary	$\dot{C}_{20} = (\dot{C}_{12} / \dot{Ex}_{12}) \times \dot{Ex}_{20}$ F-Rule
Mash Filter (MF)	
$\dot{Ex}_d$	$\dot{m}_{21} ex_{21} + \dot{m}_{14} ex_{14} + \dot{m}_{22} ex_{22} + \dot{m}_{23} ex_{23} + \dot{w}_{MF} + \dot{w}_{Air} - (\dot{m}_{24} ex_{24} + \dot{m}_{25w} ex_{25w})$
φ_{II}	$\frac{\dot{m}_{24} ex_{24} + \dot{m}_{25} ex_{25}}{\dot{m}_{21} ex_{21} + \dot{m}_{14} ex_{14} + \dot{m}_{22} ex_{22} + \dot{m}_{23} ex_{23} + \dot{w}_{MF} + \dot{w}_{Air}}$
Cost rate	$c_{21} \dot{m}_{21} ex_{21} + c_{14} \dot{m}_{14} ex_{14} + c_{22} \dot{m}_{22} ex_{22} + c_{23} \dot{m}_{23} ex_{23} + c_{wMF} \dot{w}_{MF} + c_{wAir} \dot{w}_{Air} + \dot{Z}_{MF} + \dot{C}_{hMF} = (c_{24} \dot{m}_{24} ex_{24} + c_{25} \dot{m}_{25} ex_{25})$
Auxiliary	$\dot{C}_{25w} = (\dot{C}_{24} / \dot{Ex}_{24}) \times \dot{Ex}_{25w}$ P-Rule
Holding Vessel (HV)	
$\dot{Ex}_d$	$\dot{m}_{25} ex_{25} - \dot{m}_{26} ex_{26}$
φ_{II}	$\frac{\dot{m}_{26} ex_{26}}{\dot{m}_{25} ex_{25}}$
Cost rate	$c_{25} \dot{m}_{25} ex_{25} + \dot{Z}_{HV} + \dot{C}_h = c_{26} \dot{m}_{26} ex_{26}$
Very Hot Water Tank (VHWT)	
$\dot{Ex}_d$	$\dot{m}_{28w} ex_{28w} + \dot{m}_{29w} ex_{29w} - (\dot{m}_{30w} ex_{30w} + \dot{m}_{31w} ex_{31w})$
φ_{II}	$\frac{\dot{m}_{28w} (ex_{30w} - ex_{28w})}{\dot{m}_{29w} (ex_{29w} - ex_{31w})}$
Cost rate	$c_{28w} \dot{m}_{28w} ex_{28w} + c_{29w} \dot{m}_{29w} ex_{29w} + c_{wVHWT} \dot{w}_{VHWT} + \dot{Z}_{VHWT} + \dot{C}_{hVHWT} = (c_{30w} \dot{m}_{30w} ex_{30w} + c_{31w} \dot{m}_{31w} ex_{31w})$
Auxiliary	$\dot{C}_{31w} = (\dot{C}_{29w} / \dot{E}_{29w}) \times \dot{Ex}_{31w}$ F-Rule

(Continued on following page)

TABLE 1 (*Continued*) Exergy and exergoeconomics formulations for main components in wort production.

Preheater (PHX)	
$\dot{Ex}_d$	$\dot{m}_{27}ex_{27} + \dot{m}_{28}ex_{28} - (\dot{m}_{29}ex_{29} + \dot{m}_{30}ex_{30})$
φ_{II}	$\frac{\dot{m}_{27}(ex_{29} - ex_{27})}{\dot{m}_{28}(ex_{28} - ex_{30})}$
Cost rate	$c_{27}\dot{m}_{27}ex_{27} + c_{28}\dot{m}_{28}ex_{28} + c_{wPHX}\dot{w}_{PHX} + \dot{Z}_{PHX} + \dot{C}_{hPHX} = (c_{29}\dot{m}_{29}ex_{29} + c_{30}\dot{m}_{30}ex_{30})$
Auxiliary	$\dot{C}_{30} = (\dot{C}_{28}/\dot{Ex}_{28}) \times \dot{Ex}_{30}$ F-Rule
Wort kettle: Preboiling (WKPB)	
$\dot{Ex}_d$	$\dot{w}_{WKPB} + \dot{m}_{29}ex_{29} + \dot{m}_{31}ex_{31} - (\dot{m}_{232}ex_{32} + \dot{m}_{34}ex_{34})$
φ_{II}	$\frac{\dot{m}_{232}ex_{32} + \dot{m}_{34}ex_{34}}{\dot{w}_{WKPB} + \dot{m}_{29}ex_{29} + \dot{m}_{31}ex_{31}}$
Cost rate	$c_{29}\dot{m}_{29}ex_{29} + c_{31}\dot{m}_{31}ex_{31} + c_{wWKPB}\dot{w}_{WKPB} + \dot{Z}_{WKPB} + \dot{C}_{hWKPB} = (c_{32}\dot{m}_{232}ex_{32} + c_{34}\dot{m}_{34}ex_{34})$
Auxiliary	$\dot{C}_{32} = (\dot{C}_{31}/\dot{Ex}_{31}) \times \dot{Ex}_{32}$ F-Rule
Wort kettle: Boiling and Hop Dosing (WKB)	
$\dot{Ex}_d$	$\dot{w}_{WKB} + \dot{m}_{34}ex_{34} + \dot{m}_{35}ex_{35} + \dot{m}_{36}ex_{36} - (\dot{m}_{37}ex_{37} + \dot{m}_{38}ex_{38})$
φ_{II}	$\frac{\dot{m}_{37}ex_{37} + \dot{m}_{38}ex_{38}}{\dot{w}_{WKB} + \dot{m}_{34}ex_{34} + \dot{m}_{35}ex_{35} + \dot{m}_{36}ex_{36}}$
Cost rate	$c_{34}\dot{m}_{34}ex_{34} + c_{35}\dot{m}_{35}ex_{35} + \dot{m}_{36}ex_{36} + c_{wWKB}\dot{w}_{WKB} + \dot{Z}_{WKB} + \dot{C}_{hWKB} = (c_{37}\dot{m}_{37}ex_{37} + c_{38}\dot{m}_{38}ex_{38})$
Auxiliary	$\dot{C}_{38} = (\dot{C}_{36}/\dot{Ex}_{36}) \times \dot{Ex}_{38}$ F-Rule
Wort Kettle: Stripping (WKS)	
$\dot{Ex}_d$	$\dot{w}_{WKS} + \dot{m}_{37}ex_{37} + \dot{m}_{40}ex_{40} - (\dot{m}_{39}ex_{39} + \dot{m}_{41}ex_{41})$
φ_{II}	$\frac{\dot{m}_{39}ex_{39} + \dot{m}_{41}ex_{41}}{\dot{w}_{WKS} + \dot{m}_{37}ex_{37} + \dot{m}_{40}ex_{40}}$
Cost rate	$c_{37}\dot{m}_{37}ex_{37} + c_{40}\dot{m}_{40}ex_{40} + c_{wWKS}\dot{w}_{WKS} + \dot{Z}_{WKS} + \dot{C}_{hWKS} = (c_{39}\dot{m}_{39}ex_{39} + c_{41}\dot{m}_{41}ex_{41})$
Auxiliary	$\dot{C}_{41} = (\dot{C}_{40}/\dot{Ex}_{40}) \times \dot{Ex}_{41}$ F-Rule
Wort Kettle – Overall (WKO)	
$\dot{Ex}_d$	$\dot{w}_{WKO} + \dot{m}_{29}ex_{29} + \dot{m}_{41b}ex_{41b} - (\dot{m}_{41c}ex_{41c} + \dot{m}_{41d}ex_{41d})$
φ_{II}	$\frac{\dot{m}_{41c}ex_{41c} + \dot{m}_{41d}ex_{41d}}{\dot{w}_{WKO} + \dot{m}_{29}ex_{29} + \dot{m}_{41b}ex_{41b}}$
Cost rate	$c_{29}\dot{m}_{29}ex_{29} + c_{41b}\dot{m}_{41b}ex_{41b} + c_{wWKO}\dot{w}_{WKO} + \dot{Z}_{WKO} + \dot{C}_{hWKO} = (c_{41c}\dot{m}_{41c}ex_{41c} + c_{41d}\dot{m}_{41d}ex_{41d})$
Auxiliary	$\dot{C}_{41d} = (\dot{C}_{41b}/\dot{Ex}_{41b}) \times \dot{Ex}_{41d}$ F-Rule
Whirlpool (WL)	
$\dot{Ex}_d$	$\dot{m}_{42}ex_{42} + \dot{w}_{WL} - (\dot{m}_{43}ex_{43} + \dot{m}_{44w}ex_{44w})$
φ_{II}	$\frac{\dot{m}_{43}ex_{43} + \dot{m}_{44w}ex_{44w}}{\dot{m}_{42}ex_{42} + \dot{w}_{WL}}$ (Hot break as desired product)
Cost rate	$c_{42}\dot{m}_{42}ex_{42} + c_{wwL}\dot{w}_{WL} + \dot{Z}_{WL} + \dot{C}_{hWL} = (c_{43}\dot{m}_{43}ex_{43} + c_{44w}\dot{m}_{44w}ex_{44w})$
Auxiliary	$\frac{\dot{C}_{43} - \dot{C}_{42}}{\dot{Ex}_{43} - \dot{Ex}_{42}} = \frac{\dot{C}_{44w} - \dot{C}_{42}}{\dot{Ex}_{44w} - \dot{Ex}_{42}}$ P - Rule
Wort Cooler (WC)	
$\dot{Ex}_d$	$\dot{m}_{44}ex_{44} + \dot{m}_{45}ex_{45} - (\dot{m}_{475}ex_{47} + \dot{m}_{46}ex_{46})$
φ_{II}	$\frac{\dot{m}_{44}(ex_{44} - (-ex_{46})}{\dot{m}_{45}(ex_{47} - (-ex_{45})}$ (Cold and warm exergy concept)
Cost rate	$c_{44}\dot{m}_{44}ex_{44} + c_{45}\dot{m}_{45}ex_{45} + c_{wwC}\dot{w}_{WC} + \dot{Z}_{WC} + \dot{C}_{hWC} = (c_{47}\dot{m}_{475}ex_{47} + c_{46}\dot{m}_{46}ex_{46})$
Auxiliary	$\dot{C}_{47} = (\dot{C}_{45}/\dot{Ex}_{45}) \times \dot{Ex}_{47}$ F-Rule

(Continued on following page)

TABLE 1 (*Continued*) Exergy and exergoeconomics formulations for main components in wort production.

Aerator (AE)	
$\dot{Ex}_d$	$\dot{m}_{48}ex_{48} + \dot{m}_{49}ex_{49} + \dot{w}_{AE} - \dot{m}_{50}ex_{50}$
φ_{II}	$\frac{\dot{m}_{48}(ex_{50} - ex_{48})}{\dot{m}_{49}(ex_{49} - ex_{50}) + \dot{w}_{AE}}$
Cost rate	$c_{48}\dot{m}_{48}ex_{48} + c_{49}\dot{m}_{49}ex_{49} + c_{WAE}\dot{w}_{AE} + \dot{Z}_{AE} + \dot{C}_{hAE} = c_{50}\dot{m}_{50}ex_{50}$

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (19)$$

S_N = Salvage value over the period N years and $(A/F, i, N)$ is Sinking Fund Factor (SFF) and defined by Equation 20

$$SFF = \frac{i}{(1+i)^N - 1} \quad (20)$$

The total operating costs over year N can be modelled as Equation 21 (Chan, 2007)

$$Z^{O\&M}(i) = \left\{\sum_{n=1}^{N} OC_n(P/F, i, n)\right\}(A/P, i, N) \quad (21)$$

In the absence of comprehensive O&M costs from the brewery, Equation 22 (θ = 6%, Fajardo et al., 2015; Almoghrabi and Fellah, 2022) was adopted to estimate the O&M costs of components

$$Z^{O\&M} = \theta \times PEC \quad (22)$$

Combining Equations 18, 22, the levelized total cost rate of owning, operating, and maintaining a component was then defined by Equation 23:

$$\dot{Z}_k = \frac{Z^{CI} + Z^{O\&M}}{\tau \times 3600}(USD/s) \quad (23)$$

The following key parameters were utilized in the evaluations of $\dot{Z}_k$: size exponent for component (a = 0.6); CEPCI for 2014 (204.9) and for 2019 (607.5); economic service life of brewing component (N = 10 years); attractive rate of return, i = 12%; $TCI = 1.55 \times PEC$; $S_N = 0.155 \times PEC$; annual operating hours, $\tau = 8000$. The components involved in the storage, extraction, and milling of grains do not experience exergetic changes as the thermomechanical properties of the streams remain constant at the boundaries of these components. Thus, in the milling room, the premasher stands as the sole component amenable to cost evaluation based on the exergetic values of its streams resulting from hot hydration of the brewing grist.

2.8.3 Formulation of exergy costing and auxiliary equations

The cost rate and auxiliary cost equations are used to evaluate the costs related with materials and energy streams associated to a productive component. Generally, the cost rates for upstreams are considered known so as to evaluate product cost of processed stream within a component. The generalized Equation 24, for cost rates associated with a component, k, was defined based on Specific Exergy Costing (SPECO) methodology, as defined in Bejan et al. (1996):

$$\dot{Z}_k + \dot{C}_{w,k} + \sum_i \dot{C}_{i,k} = \dot{C}_{q,k} + \sum_e \dot{C}_{e,k} \quad (24)$$

Where, $\dot{C}_{w,k} = c_w\dot{W}_{cv}$; $\dot{C}_{i,k} = c_i\dot{Ex}_i$; $\dot{C}_{q,k} = c_q\dot{Ex}^q$; and $\dot{C}_{e,k} = c_e\dot{Ex}_e$

The exergy rates ($\dot{W}_{cv}, \dot{Ex}_i, \dot{Ex}_e and\ \dot{Ex}^q$) were evaluations done in exergetic analyses. The average unit cost of fuel ($c_{F,k}$) and product ($c_{P,k}$) as concern a system component, k, were defined as $c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{Ex}_{F,k}}$ and $c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{Ex}_{P,k}}$ respectively.

Formulation of an auxiliary cost equation is only necessary for components with more than one exit stream. Based on the F and P principles defined in Lazzaretto and Tsatsaronis (2006), Table 1 shows the exergetic, cost rate and auxiliary equations for the main components in the wort production. When evaluating the cost rate of streams, $\dot{C}_j$ the following average costs per unit of exergy of utilities were adopted: electricity supply, $c_W = 0.035\,USD/MJ$; steam supply, $c_{steam} = 0.022\,USD/MJ$; hot water supply, $c_{hotwater} = 0.01815\,USD/MJ$; chilled water supply, $c_{chilledwater} = 0.0016\,USD/MJ$ (Intractec, 2019). Moreover, the average cost rate for human energy expenditure depends on the average monthly pay of assigned employees in the process line, $\dot{C}_h = 0.0006\,USD/s$.

2.8.4 Formulation of exergoeconomic performance variables

The variables were defined by Equations 25–27 as presented in Bejan et al. (1996) and are utilized in this study:

$$\text{Cost rate of exergetic destruction } \dot{C}_{D,k} = c_{F,k}\dot{Ex}_{D,k}\left(\dot{Ex}_{P,k}\text{ fixed}\right) \quad (25)$$

$$\text{Relative cost difference, } r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{1 - \varphi_{II,k}}{\varphi_{II,k}} + \frac{\dot{Z}_k}{c_{F,k}\dot{Ex}_{P,k}} \quad (26)$$

$$\text{Exergoeconomic factor, } f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}\left(\dot{Ex}_{D,k} + \dot{Ex}_{l,k}\right)} \quad (27)$$

3 Results and discussion

MS Excel and Engineering Equation Solver (EES) were the tools used to model, process data, and generate performance values for system components.

3.1 Total energy consumption pattern for the wort production system

For the studied site, 1950 kg adjunct maize grains, 800 kg adjunct malted barley, and 7300 kg malted barley, are fed into the milling room and processed into premashed products. Each brew produces 346.98 hL of high-gravity wort at the brewhouse.

TABLE 2 Consumption values and standard deviations for components in the brewhouse.

Comp	E^e (MJ)	δ_e (MJ)	E^h (MJ)	δ_h (MJ)	E^q (MJ)	δ_q (MJ)	E^{tot} (MJ)	δ_{tot} (MJ)
AK	29.1600	0.9072	0.3645	0.0113	1,362.1175	10.5680	1,391.6420	10.6069
AKP	4.7026	0.1025					4.7026	0.1025
MT	51.2963	0.9539	0.6534	0.0135	3630.9270	20.3999	3682.8767	20.4222
MTP	5.9162	0.1575					5.9162	0.1575
MF	784.6992	16.2097	1.1097	0.0324	2884.1925	140.4954	3670.0014	141.4275
WP	17.9626	0.5573					17.9626	0.5573
HV	0.0000	0.0000					0.0000	0.0000
HVP	16.9642	0.7959					16.9642	0.7959
PHX	0.0000	0.0000			5,341.4127	145.8307	5,341.4127	145.8307
WKO	96.5477	2.0433	0.2916	0.0097	9,967.7004	44.7874	10,064.5397	44.8340
WKP	20.6812	1.3245					20.6812	1.3245
WL	15.7680	0.6749	0.3645	0.0113			15.7680	0.6749
WLP	19.0270	0.5708					19.0270	0.5708
WC	0.0000	0.0000					0.0000	0.0000
WCP	54.8268	0.1935					54.8268	0.1935
AE	0.0000	0.0000					0.0000	0.0000
Tot	1,117.5518	16.4990	2.4192	0.0381	23,186.3501	208.6607	24,306.3212	209.3120

TABLE 3 Results of thermal energy efficiency and exergetic performances of milling room components.

Comp	φ_k (%)	$\dot{W}_{cv}$ (MW)	$\dot{E}_f$ (MW)	$\dot{E}_p$ (MW)	$\dot{E}_d$ (MW)	φ_{II} (%)	$\dot{y}_d$	SI	IP (MW)
DMG		0.0110			0.0110		0.0308		0.0110
TMG		0.0176			0.0176		0.0493		0.0176
DAG		0.0003			0.0003		0.0008		0.0003
SAP		0.0015			0.0015		0.0041		0.0015
LMG		0.0045			0.0045		0.0125		0.0045
LAG		0.0003			0.0003		0.0008		0.0003
DSG		0.0013			0.0013		0.0035		0.0013
DML		0.0006			0.0006		0.0016		0.0006
DDG		0.0018			0.0018		0.0049		0.0018
HM		0.1762			0.1762		0.4931		0.1762
MGH		0.0071			0.0071		0.0198		0.0071
AGH		0.0015			0.0015		0.0043		0.0015
PMG-a	84.6143	0.0138	0.0609	0.0399	0.0349	53.36	0.0990	2.1443	0.0162
PMG-b	84.6725	0.0138	0.0609	0.0414	0.0337	55.39	0.0947	2.2416	0.0149
PMG-c	49.6612	0.0138	0.0609	0.0147	0.0600	19.62	0.1707	1.2441	0.0483
PMG	75.7015	0.0138	0.1828	0.0959	0.1286	48.78	0.3644	1.9523	0.0516
Overall		0.2648	0.1828	0.0959	0.3522	21.42		1.2726	0.2764

TABLE 4 Thermodynamic properties of process streams of the brewhouse.

Str	Stream type	T (K)	P (MPa)	$\dot{m}$ (kg/s)	C_p (kJ/kg.K)	h (kJ/kg)	s (kJ/kg.K)	*ex* (kJ/kg)
3a	Premash Adj. Maize	338.65	0.039	4.374	3.632	237.9258	21.1589	9.1123
3b	Premash Adj. Malt	338.65	0.393	4.527	3.512	230.0507	20.4586	9.1385
4	Wet Steam	410.97	0.340	0.556		2,724.5120	6.9360	661.0747
5	Hot water (cooking)	352.65	0.152	3.252	4.180	334.5100	1.0743	18.7385
6	Hot water (rinsing)	352.65	0.152	3.252	4.180	334.5100	1.0743	18.7385
7	Addictive – lime	298.15	0.100	0.500				
8	Addictive - CaSO4	298.15	0.100	0.500				
9	Cooked Adjunct	361.55	0.300	12.153	3.683	325.5687	21.6938	21.9798
10	Condensate return	366.65	0.080	0.556		564.0000	1.6466	78.4773
11	Cooked Adjunct	361.65	0.420	12.153	3.683	325.9370	21.6948	22.1586
12	Wet Steam	410.97	0.340	0.556		2,724.5120	6.9360	660.0747
13	Hot Water (cooking)	352.65	0.152	3.252	4.186	334.5100	1.0743	18.7385
14	Hot Water (To MF)	352.55	0.250	3.252	4.186	332.7600	1.0743	16.9885
3c	Premashed Malt	320.25	0.393	5.182	3.298	155.3204	19.0246	2.8280
15	Addictive - CaSO4	298.15	0.100	0.500				
16	Addictive - CaCl2	298.15	0.100	0.500				
17	Addictive - H3PO4	298.15	0.100	0.500	0.000			
18	Addictive - Laminex	298.15	0.100	0.500				
19	Mashed Product	353.05	0.020	23.839	3.518	281.1271	20.6416	15.7895
20	Condensate	366.65	0.080	0.556	4.186	564.0000	1.6466	77.5973
21	Mashed Product	353.05	0.090	23.839	3.518	281.1271	20.6416	15.8548
22	Hot Water/Sparging	349.15	0.250	6.111	4.186	317.9640	1.0280	15.9969
23	Compressed Air	303.15	0.700	0.106	1.006	304.9689	1.1539	166.5975
24	Wort	349.75	0.101	20.243	3.839	294.0299	22.4830	15.3885
25w	Spent Grain	349.15	0.000	12.959	3.512	266.9234	20.5654	13.6747
25	Wort	349.75	0.145	20.243	3.839	294.0299	22.4830	15.4305
26	Wort	349.15	0.110	20.243	3.764	286.0885	22.0420	14.7681
27	Wort	349.15	0.285	20.243	3.764	286.0885	22.0420	14.9351
28w	Hot Water	350.25	0.152	19.794		323.1000	1.0400	17.6560
29w	Wet Steam	410.97	0.340	0.416		2,724.5120	6.9360	661.0747
30w	Very Hot Water	394.55	0.208	19.794		426.4900	1.3300	34.6260
31w	Condensate	366.65	0.110	0.416		564.0000	1.6466	77.7892
28	Very Hot Water	410.97	0.340	11.600		580.2900	1.7186	72.6232
29	Wort	371.95	0.250	20.243	3.784	373.8885	22.3983	29.8935
30	Hot Water	351.25	0.300	11.600		328.7400	1.0574	18.1108
31	Wet Steam	410.97	0.340	0.656		2,724.5120	6.9360	661.0747
32	Condensate	366.65	0.110	0.656		564.0000	1.6466	77.7892
33	Wort	374.20	0.125	20.243	3.787	382.6274	22.4343	31.4989

(Continued on following page)

TABLE 4 (*Continued*) Thermodynamic properties of process streams of the brewhouse.

Str	Stream type	T (K)	P (MPa)	$\dot{m}$ (kg/s)	C_p (kJ/kg.K)	h (kJ/kg)	s (kJ/kg.K)	*ex* (kJ/kg)
34	Wort (Boiling)	374.20	0.125	20.243	3.787	382.8167	22.4343	31.6882
35	Hops Dosing	301.15	0.100	0.009	1.842			0.0000
36	Wet Steam	410.97	0.340	1.093		2,724.512	6.9360	661.0747
37	Wort (Dosed)	374.20	0.125	20.243	3.835	387.5595	22.7187	32.0072
38	Condensate	364.35	0.110	1.093		383.51	1.2111	26.9516
39	Wort	375.35	0.101	20.243	3.835	393.0373	22.7304	33.9261
40	Wet Steam	410.97	0.345	0.546		2,724.5120	6.9360	661.0747
41	Condensate	358.75	0.110	0.546		399.8500	1.1462	62.7584
42	Wort	375.35	0.340	20.243	3.835	393.0373	22.7304	34.1620
43	Hot Wort	368.95	0.124	11.980	3.769	361.0777	22.2777	25.2491
44w	Trub (Hot Breaks)	366.75	0.124	8.263	2.354	220.3222	13.8989	16.1638
44	Hot Wort	368.95	0.180	11.980	3.773	361.7928	22.2996	25.4124
45	Chilled Water	276.25	0.29	18.652		13.0529	0.0474	3.4516
46	Cold Wort	283.95	0.100	11.980	3.714	40.1067	20.9773	1.2971
47	Hot Water	356.27	0.080	18.652	4.189	348.0690	1.1123	20.9678
48	Cooled wort	283.95	0.400	11.980	3.714	40.1067	20.9773	1.5812
49	Oxygen	288.35	0.380	0.0002		262.3600	6.0299	0.0100
50	Oxygenated Wort	283.95	0.400	10.120	3.717	40.1067	20.9773	1.5812

3.1.1 Energy consumptions for components in the milling room

The cumulative specific energy was estimated as (15.8 ± 0.2) MJ/hL with 84.09% and 15.85% thermal and electrical energy contributions respectively. The hammer miller was pinpointed as the top consumer of electricity with estimated value of (700 ± 20) MJ and distantly followed by the premasher (50 ± 2) MJ. The premasher is responsible for all the heating load of the milling room with an overall thermal energy input of (5,000 ± 30) MJ. The overall thermal efficiency of the premasher was evaluated as 74.45%. Notably, the destoner (0.74 ± 0.01) MJ, pit system (0.58 ± 0.02) MJ, and hammer miller (0.6 ± 0.1) MJ are top consumers of human energy.

3.1.2 Energy consumption for components in the brewhouse

Table 2 presents the energy pattern for components of the brewhouse. The electrical, thermal and cumulative energy intensities for the section are respectively computed as (3.2 ± 0.1) MJ/hL, (67 ± 1) MJ/hL and (70 ± 1) MJ/hL. The wort kettle was the biggest consumer with an estimated total energy intensity value of (29.0 ± 0.7) MJ/hL.

Table 2 also indicates that the wort kettle and preheater were the highest consumers of total energy, accounting for 41.38% and 21.96% respectively. The mash filter and wort kettle were the top electricity users. The section's thermal efficiency was measured at 27.41%, with the wort kettle and preheater contributing to 60.66% of the supplied thermal energy.

3.1.3 Overall energy consumption pattern

The energy consumption analysis for the production system revealed that the total specific energy for a 346.98 hL high-gravity brew was (86 ± 1) MJ/hL at an operational energy efficiency of 30.35%. This energy was derived from electrical (5.7 ± 0.2) MJ/hL, thermal (80 ± 1) MJ/hL, and manual (0.017 ± 0.002) MJ/hL sources. The brewhouse accounted for the largest portion of energy consumption, representing 56.35% of electrical energy, 83.47% of thermal energy, and 81.66% of the total energy input. The milling room was the primary source of human energy input, contributing 57.28% to the total human input.

3.2 Exergetic performances of the wort production system

The main brewing feedstock handled in the milling room does not undergo significant temperature and pressure changes as they moved from the pit system through the hammer miller to the premasher. The premasher, however, involves hydration of the feedstock at a temperature well above the dead state; hence, the premasher is the only milling room component with considerable exergetic changes between input and output streams. In effect, the useful works of all milling room components, except that of the premasher, are all considered exergetic destructions since no exergetic changes are noticeable in the product stream across the components.

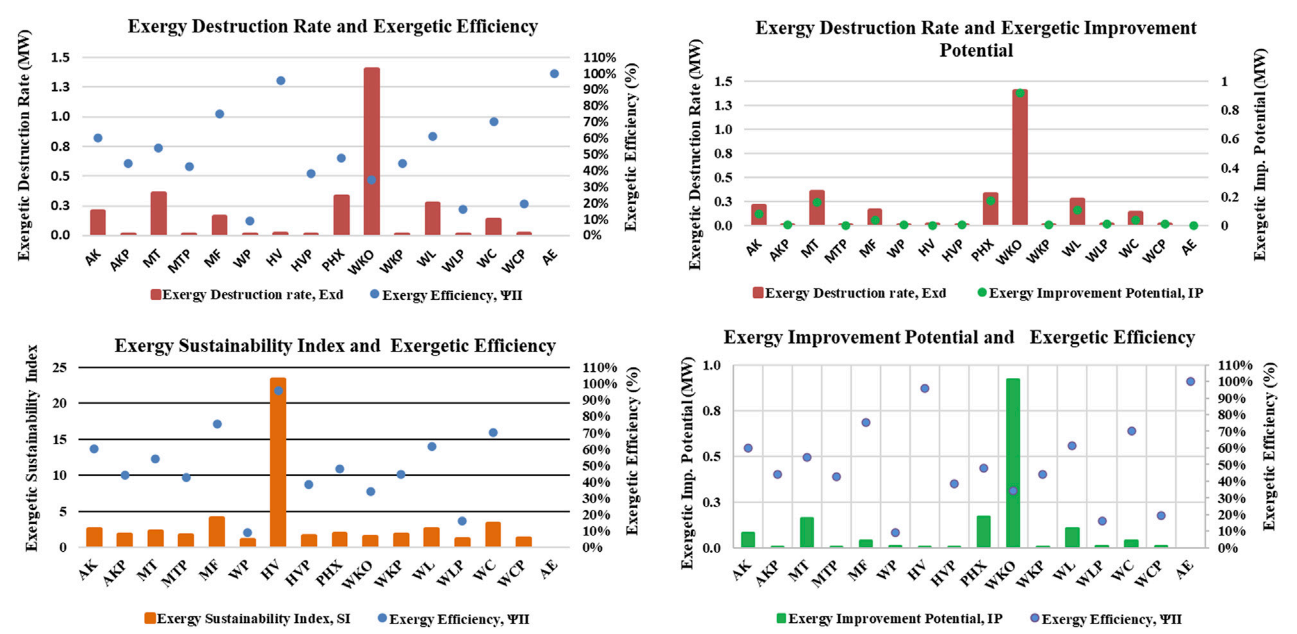

FIGURE 2
An exergetic performance dashboard for production components in the brewhouse.

TABLE 5 Results of thermal efficiency and exergetic indicators of components in the brewhouse.

Comp	φ_k (%)	$\dot{W}$ (MW)	$\dot{E}_f$ (MW)	$\dot{E}_p$ (MW)	$\dot{E}_d$ (MW)	φ_{II} (%)	$\dot{y}_d$	SI	IP (MW)
AK	88.4752	0.0061	0.5094	0.3102	0.2053	60.1791	0.0588	2.5112	0.0817
AKP	100.0000	0.0049		0.0022	0.0027	44.2462	0.0007	1.7936	0.00397
MT	78.7841	0.0060	07,674	0.4200	0.3538	54.2458	0.1014	2.1856	0.1619
MTP	100.0000	0.0037		0.0016	0.0021	42.6093	0.0006	1.7424	0.0012
MF	93.7741	0.1025	0.5473	0.4887	0.1611	75.2076	0.0462	4.0335	0.0399
WP	100.0000	0.0093		0.0009	0.0085	9.1143	0.0024	1.1003	0.0077
HV	96.9269		0.3124	0.2990	0.0134	95.7074	0.0037	23.2959	0.0006
HVP		0.0088		0.0034	0.0054	38.3834	0.0015	1.6229	0.0033
PHX	60.5633		0.6324	0.3027	0.3296	47.8763	0.0945	1.9185	0.1718
WKPB	83.0219	0.0177	1.0355	0.6925	0.3608	65.7469	0.1235	2.9194	0.1236
WKB	71.2623	0.0177	1.3647	0.6773	0.7051	48.9966	0.2413	1.9607	0.3596
WKS	83.6758	0.0177	1.0223	0.7223	0.3177	69.4520	0.1087	3.2735	0.0971
WKO	56.3354	0.0177	2.1190	0.7358	1.4009	34.4378	0.4794	1.5253	0.9184
WKP	100.0000	0.0108		0.0048	0.0060	44.3829	0.0016	1.7980	0.0033
WL	74.6623	0.0175	0.6916	0.4361	0.2730	61.4610	0.0839	2.5971	0.1051
WLP		0.0120		0.0020	0.0100	16.3023	0.0031	1.1948	0.0084
WC	90.2439	0.0000	0.4555	0.3200	0.1355	70.2528	0.0417	3.3617	0.0403
WCP	100.0000	0.0176		0.0034	0.0142	19.3727	0.0044	1.2403	0.0114
AE		0	0.0189	0.0189	0.0000	1.0000	0.0000		0.0000
Overall	13.3588	0.2172	2.5803	0.1961	2.9219	7.0116		1.0754	2.4189

TABLE 6 Exergy and cost rates for all streams in the wort production line.

Stream no.	Stream descriptions	Exergy rate, Ex (MJ/s)	Average cost per unit of exergy, c (USD/MJ)	Cost rate, $\dot{C}\,(USD/s)$
Milling Room Exergy and Cost Rates				
1a	Hot Water	0.0609	0.0181	0.0011
2a	Adjunct Maize Grist	0.0000	-	
3a	Premashed Adjunct Maize	0.0399	0.0449	0.0029
C_{wMGa}	Electricity	0.0138	0.0350	0.0005
C_h	Human power (2 persons; t = 0.36 h)			0.0006
1b	Hot Water	0.0609	0.0181	0.0011
2b	Adjunct Malt Grist	0.0000	-	
3b	Premashed Adjunct Malt	0.0414	0.0435	0.0030
C_wMGb	Electricity	0.0141	0.0350	0.0005
C_h	Human power (2 persons; t = 0.15 h)			0.0006
1c	Hot Water	0.0609	0.0181	0.0011
2c	Malt grist	0.0000	-	
3c	Premashed Malt	0.0147	0.1219	0.0029
C_wMGc	Electricity	0.0137	0.0350	0.0005
C_h	Human power (2 persons; t = 0.57 h)			0.0006
C_1	C_1a + C_1b + C_1c	0.0000		0.0033
C_3	C_1 + C_wMG + Z_MG	0.0000		0.0040
C_wMG	Electricity	0.0416	0.0350	0.0015
Brewhouse Exergy and Cost Rates				
3a	Premashed Adj. Maize	0.0399	0.0449	0.0029
3b	Premashed Adj. Malt	0.0414	0.0435	0.0030
4	Wet Steam	0.3673	0.0220	0.0079
5	Hot water (cooking)	0.0609	0.0181	0.0011
6	Hot water (for rinsing)	0.0609	0.0181	0.0011
7	Addictive - lime	0.0000	-	-
8	Addictive - CaSO4	0.0000	-	-
9	Cooked Premashed Adjunct	0.2671	0.0584	0.0185
10	Condensate Return	0.0431	0.0181	0.0008
C_wAK		0.0061	0.0350	0.0002
C_{hAK}	Human power (1 person; t = 1.35 h)			0.0006
11	Cooked Adjunct	0.2693	0.0612	0.0193
C_wAKP		0.0049	0.0350	0.0002
12	Wet Steam	0.3673	0.0220	0.0081
13	Hot Water for cooking	0.0609	0.0181	0.0011

(Continued on following page)

TABLE 6 (*Continued*) Exergy and cost rates for all streams in the wort production line.

Stream no.	Stream descriptions	Exergy rate, Ex (MJ/s)	Average cost per unit of exergy, c (USD/MJ)	Cost rate, $\dot{C}\,(USD/s)$
14	Hot Water (To Mash Filter)	0.0552	0.0182	0.0010
3c	Premashed Malt	0.0147	0.1219	0.0030
15	Addictive - CaSO4	0.0000		-
16	Addictive - CaCl2	0.0000		-
17	Addictive - H3PO4	0.0000		-
18	Addictive - Laminex	0.0000		-
19	Mashed Product	0.3764	0.0861	0.0371
20	Condensate Return	0.0431	0.0220	0.0009
C_wMT		0.0060	0.0350	0.0002
C_{hMT}	Human power (1 person; t = 2.42 h)			0.0006
21	Mashed Product	0.3780	0.0875	0.0376
C_wMTP		0.0037	0.0350	0.0001
22	Hot Water (Sparging)	0.0978	0.0181	0.0018
23	Compressed Air	0.0176	0.0000	0.0000
24	Wort	0.3115	0.1191	0.0408
25w	Spent Grain	0.1772	0.1191	0.0232
C_wMF		0.1025	0.0350	0.0036
C_{hMF}	Human power (2 persons; t = 2.13 h)			0.0006
25	Wort	0.3124	0.1221	0.0419
C_wWP		0.0093	0.0350	0.0003
26	Wort	0.2990	0.1389	0.0453
C_wHV				0.0000
27	Wort	0.3023	0.1407	0.0463
C_wHVP		0.0088	0.0350	0.0003
28w	Hot Water	0.3332	0.0000	
29w	Wet Steam	0.8475	0.0000	
30w	Very Hot Water	0.6534	0.0000	
31w	Condensate	0.0997	0.0000	
28	Very Hot Water	0.8424	0.0181	0.0153
29	Wort	0.6051	0.0896	0.0579
30	Hot Water	0.2101	0.0181	0.0038
31	Wet Steam	0.4334	0.0219	0.0095
32	Condensate	0.0510	0.0220	0.0011
C_wWKPB		0.0177	0.0350	0.0006
C_{hWKPB}	Human power (1 person; t = 0.51 h)			0.0006
33	Wort	0.6376	0.0000	

(Continued on following page)

TABLE 6 (*Continued*) Exergy and cost rates for all streams in the wort production line.

Stream no.	Stream descriptions	Exergy rate, Ex (MJ/s)	Average cost per unit of exergy, c (USD/MJ)	Cost rate, $\dot{C}$ (USD/s)
34	Wort	0.6398	0.1089	0.0728
35	Hops Dosing	0.0000		
36	Wet Steam	0.7233	0.0220	0.0159
37	Wort (Dosed)	0.6479	0.1406	0.0945
38	Condensate	0.0294	0.0220	0.0006
C_wWKB		0.0177	0.0350	0.0006
C_{hWKB}	Human power (1 person; t = 1 h)			0.0006
39	Wort (To Whirlpool)	0.6868	0.1648	0.1084
40	Wet Steam	0.3744	0.0220	0.0082
41	Condensate	0.0355	0.0220	0.0008
c_wWKS		0.0177	0.0350	0.0006
C_{hWKS}	Human power (1 person; t = 0.10 h)			0.0006
41b	Total steam used	1.5168	0.0220	0.0334
41c	Wort (Dosed, To Whirlpool)	0.6868	0.1513	0.0979
41d	Total Condensate recovered	0.0490	0.0220	0.0011
C_wWKO		0.0177	0.0350	0.0006
42	Wort (Dosed, To Whirlpool)	0.6916	0.1653	0.1095
C_wWKP		0.0115		0.0004
43	Hot Wort into Chiller	0.3025	0.2295	0.0668
44w	Trub (Hot Breaks)	0.1336	0.3738	0.0483
C_wWL		0.0175	0.0350	0.0006
C_{hWL}	Human power (1 person; t = 0.25 h)			0.0006
44	Hot Wort into Chiller	0.3044	0.2321	0.0681
C_wWLP		0.0120	0.035	0.0004
45	Chilled Water	0.0644	0.0076	0.0005
46	Cold Wort out of WC	0.0155	4.4191	0.0661
47	Hot Water	0.3911	0.0076	0.0030
48	Cooled wort	0.0189	3.7155	0.0678
C_wWCP		0.0176	0.0350	0.0005
49	Oxygen	0.0000	475.5238	0.0000
50	Chilled wort	0.0079	0.0000	0.0681

3.2.1 Exergetic performance for components in the milling room

In Table 3, the premasher's thermal and overall exergetic efficiencies are estimated to be 75.70% and 48.78% respectively. There is an improvement potential of 0.0516 MW and an exergetic destruction rate of 0.1286 MW, which constituted 36.55% of the overall exergetic destruction rate for the milling room. The milling room's exergetic efficiency, exergetic improvement potential, and exergetic sustainability index were evaluated as 21.42%, 0.2764 MW, and 1.2726, respectively.

3.2.2 Exergetic performance indicators for components in the brewhouse

The thermodynamic properties of the process streams of the brewhouse are shown in Table 4. In Table 5, the brewhouse exergetic performances showed that the destruction rate, efficiency,

TABLE 7 Results of exergoeconomic analyses for components in the wort production line.

Comp	$\dot{W}$ (MW)	$\dot{Ex}_{f,k}$ (MW)	$\dot{Ex}_{p,k}$ (MW)	$\dot{Ex}_D$ (MW)	$c_{f,k}$ (USD/MJ)	$c_{P,k}$ (USD/MJ)	$\dot{C}_{D,k}$ (USD/h)	$\dot{Z}_k$ (USD/h)	$\dot{C}_{D,k} + \dot{Z}_k$ (USD/h)	r_k (–)	f_k (%)
PMG-a	*0.0138*	*0.0609*	*0.0399*	*0.0348*	*0.0213*	*0.0750*	*2.6677*	*0.5750*	*3.2428*	*2.5261*	*17.7332*
PMG-b	*0.0138*	*0.0609*	*0.0414*	*0.0333*	*0.0148*	*0.0725*	*1.7763*	*0.5750*	*2.3513*	*3.8972*	*24.4565*
PMG-c	*0.0138*	*0.0609*	*0.0147*	*0.0600*	*0.0148*	*0.2040*	*3.2002*	*0.5750*	*3.7754*	*12.7777*	*15.2315*
PMG	0.0138	0.1828	0.0959	0.1282	0.0169	0.0936	7.7895	1.7251	9.5146	4.5448	18.1315
MF	0.1025	0.5473	0.4887	0.1611	0.0677	0.1311	39.2399	67.9833	107.2233	0.9374	63.4035
WP	0.0093	-	0.0009	0.0085	0.0345	1.2117	1.0535	2.6665	3.7200	34.0962	71.6792
HV		0.3124	0.2990	0.0134	0.1340	0.1514	6.4688	12.1048	18.5736	0.1297	65.1721
HVP	0.0088	-	0.0034	0.0054	0.0366	0.1898	0.7143	2.6665	3.3808	4.1914	78.8728
PHX	-	0.6324	0.3027	0.3296	0.0181	0.0385	21.5361	0.7597	22.2958	1.1238	3.4074
WKPB	*0.0177*	*1.0355*	*0.6925*	*0.3608*	*0.0647*	*0.1067*	*83.9916*	*18.8844*	*102.8759*	*0.6505*	*18.3564*
WKB	*0.0177*	*1.3647*	*0.6773*	*0.7051*	*0.0646*	*0.1404*	*164.0015*	*18.8844*	*182.8859*	*1.1737*	*10.3258*
WKS	*0.0177*	*1.0223*	*0.7223*	*0.3177*	*0.0994*	*0.1512*	*113.6419*	*18.8844*	*132.5262*	*0.5213*	*14.2495*
WK	0.0177	2.1190	0.7358	1.4009	0.1212	0.1345	361.6350	18.8844	418.2881	0.1102	4.5147
WKP	0.0108	-	0.0048	0.0060	0.0374	0.2304	0.8059	2.7090	3.5149	5.1576	77.0718
WL	0.0179	0.6916	0.4361	0.2734	0.1552	0.2641	152.7707	15.9126	168.6833	0.7013	9.4334
WLP	0.0120	-	0.0020	0.0100	0.0350	0.6236	1.2655	2.7090	3.9745	16.8181	68.1591
WC	0.0000	0.4555	0.3200	0.1355	0.0076	0.4192	3.7067	1.7429	5.4496	54.1640	31.9819
WCP	0.0176	-	0.0034	0.0142	0.0297	0.5025	1.5137	4.1060	5.6198	15.9279	73.0645
AE	0.0000	0.0189	0.0189	0.0000	3.9015	3.9155	–0.0039	0.9778	0.9739	0.0036	100.3672

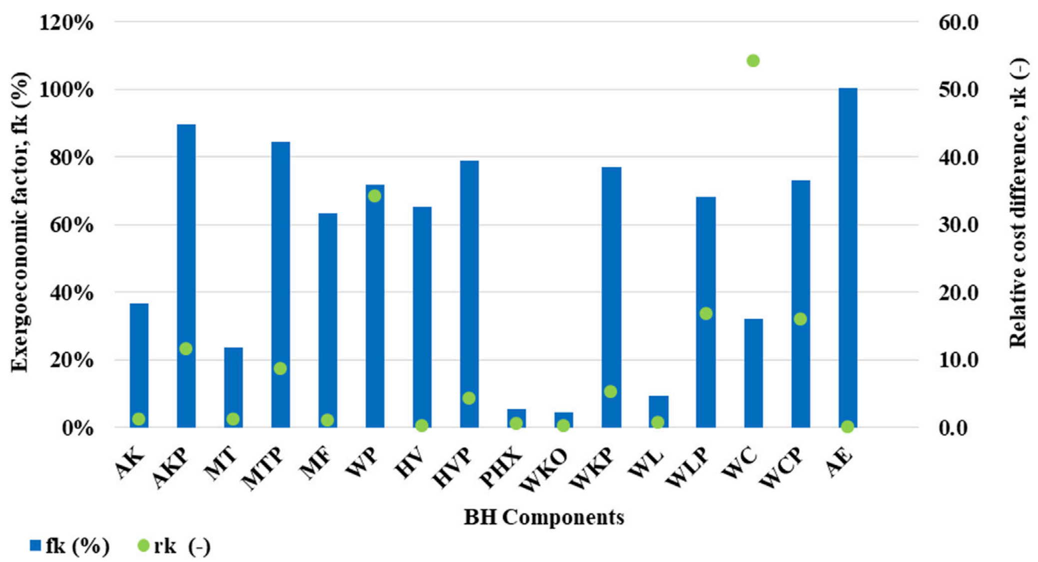

FIGURE 3
Exergoeconomic factor and relative cost difference for components of the brewhouse.

improvement potential rate, and sustainable index were 2.9219 MW, 7.0116%, 2.4189 MW and 1.0754, respectively. The wort kettle had the highest destruction rate distantly followed by the mash tun and wort preheater. During wort stripping, there is rapid heat transfer from the kettle to the wort, leading to high exergy destruction. The finite temperature differential between the steam and surroundings during wort boiling also increases irreversibility. Also, the wort experienced a remarkable drop in exergetic value due to the exergy loss accompanying the 5% water content stripped off. This exergy cannot be accounted for since the stripped-off content is not captured or reused. Even though the first heating process, wort pre-boiling, has the least exergy destruction rate, there is a potential to avoid this destruction if the exit temperature of the wort from the preheater increased to the needed wort boiling temperature.

Thus, thermal insulation of the wort kettle based on its economic viability should be of interest in the optimization efforts for the component. The lowest destruction rates were found in the pumps with a total percentage of 1.66%. The wort pump WP, wort whirlpool pump WLP, and wort cooler pump WCP, were the least efficient components in the brewhouse with exergetic efficiencies of 9.11%, 6.30%, and 19.37%, respectively.

The holding vessel, mash filter, and wort cooler were the main components with the most efficient exergetic efficiencies of 95.71%, 75.21%, and 70.25%, respectively. The contribution of the pumps to the brewhouse's exergetic destruction rate was found to be insubstantial based on their functional exergetic efficiency values. The cumulative exergy destruction ratio of the three pumps was only 1.01%. The low exergy destruction ratio and functional efficiency of the pumps indicated that their inefficiencies stemmed from oversized mechanical work inputs from the electric motors powering the pumps, rather than from external irreversibility.

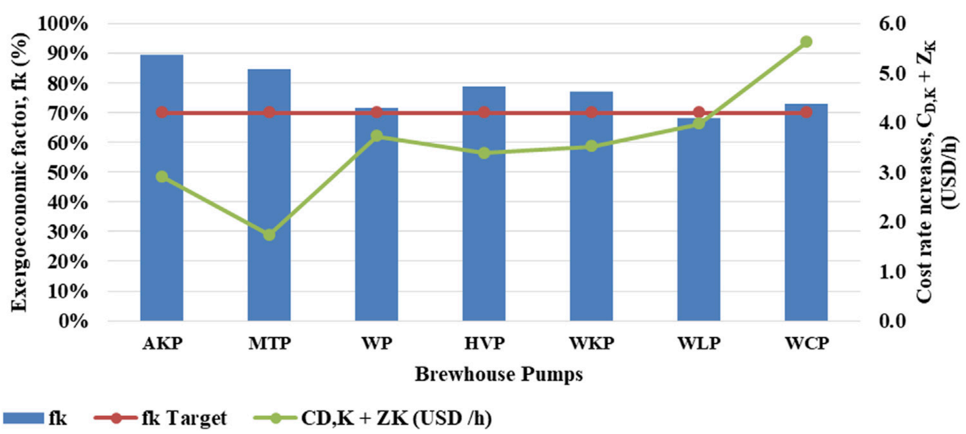

FIGURE 4
Performances of each brewhouse pumps against typical pump benchmark, $f_k > 70$.

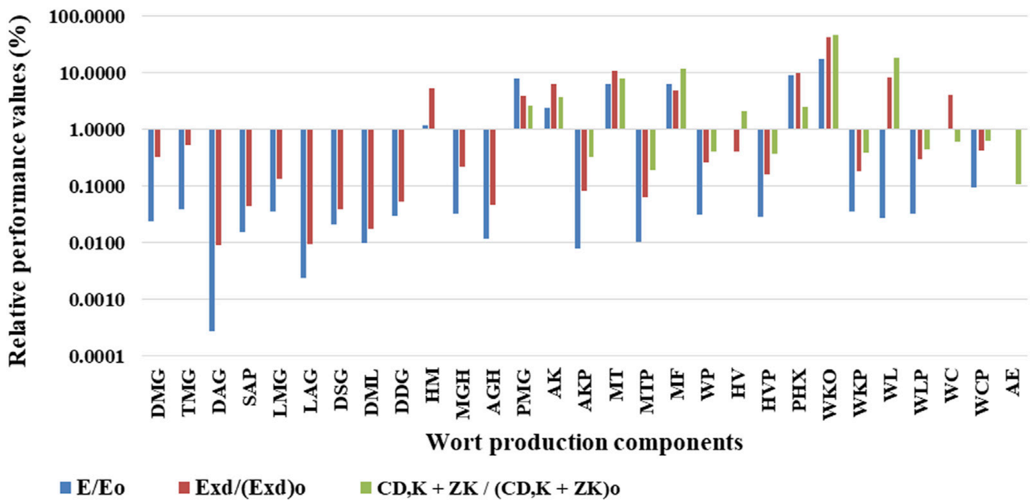

FIGURE 5
Relative performances of components in wort production line.

Therefore, utilizing well-sized motors that supply the required pressure head for the wort transfers would enhance the pump's exergetic efficiency.

Improving the exergetic efficiencies of the wort kettle (34.44%), preheater (47.88%) and the mash tun (54.25%) will significantly raise the brewhouse efficiency. While thermal insulation and throttling of the wet steam, so that steam heating is done at the programmed specific enthalpy of 2,724.51 kJ/kg and at a considerably lower temperature, provide substantial improvements of the kettle and tun, a pressure controller provides good improvement in the preheater's efficiency. The mash filter and wort cooler, despite demonstrating relatively high exergetic efficiencies, remain contributors to the overall brewhouse exergy destruction, comprising 9.12% of the total. This suggests potential for further improvement. The exergetic heat loss of the mash filter can be attributed to the sparging process, specifically the substantial heat release during the initial 5–7 min. Proposed solutions encompass the exploration of a retrofit heat recovery system and the reduction of sparging cycle duration. Regarding the wort cooler, the predominant source of external irreversibility is the heat transfer between the cold exergy of the chilled water and the hot exergy of the hot wort, as well as heat absorption from the surroundings.

Figure 2 dashboard shows exergetic indicators and reflects that high destruction rates indicate low sustainability index and great potential for improvement. Components with higher destruction rates have higher improvement potentials. However, while the preheater has a lower destruction rate than the mash tun, its potential for improvement is higher. Optimization potentials for the preheater were proposed in Section 3.4.2. The holding vessel, mash filter, and wort cooler were top performers, with high exergetic sustainability indices and efficiencies.

3.2.3 Overall exergetic performances of the wort production system

The exergetic destruction rate for wort production was calculated at 3.2737 MW, with a specific destruction rate of 9.4348 kW/hL and an operational exergetic efficiency of 6.61%. The potential for exergetic improvement was estimated at 2.5861 MW, with brewhouse operations identified as the cause of 89.25% of production inefficiencies.

3.3 Exergoeconomic analyses and performance indicators for system components

This section and its subsections assessed the exergoeconomic variables critical for the analyses of production line components. The objectives included understanding how cost rates were formed, identifying significant components and potential adjustments, and providing valuable data for improvements. To determine which components impact a section the most, the sum of the cost rates for exergy destruction rate and the capital investment and O&M ($\dot{C}_{D,k} + \dot{Z}_k$) was ranked in descending order. The highest ranked component is the most relevant for exergoeconomic evaluation. The exergoeconomic factor f_k pinpoints the aspect of the total cost rate responsible for component inefficiency. A high value indicates inefficiency attributable to capital investment and O&M cost ($\dot{Z}_k$) while a low value attributes inefficiency to exergy destruction. Table 6 presents exergetic and cost rate formation for all streams in the wort production. The average cost rate for the conversion of 10.05 tons of brewing grains into high gravity wort of 346.98 hL was estimated at 0.0681 USD/s.

3.3.1 Exergoeconomic performance indicators for components of the milling room

The first three rows, italicized, in Table 7 show the exergoeconomic variables of the three processes carried out in the premasher. The fourth row expresses the overall effects of the processes for the component. The premashing of the malt grist had the most significant total cost increase of the three processes; therefore, from an exergoeconomic standpoint, this process is the most relevant for the component. The r_k value confirms the

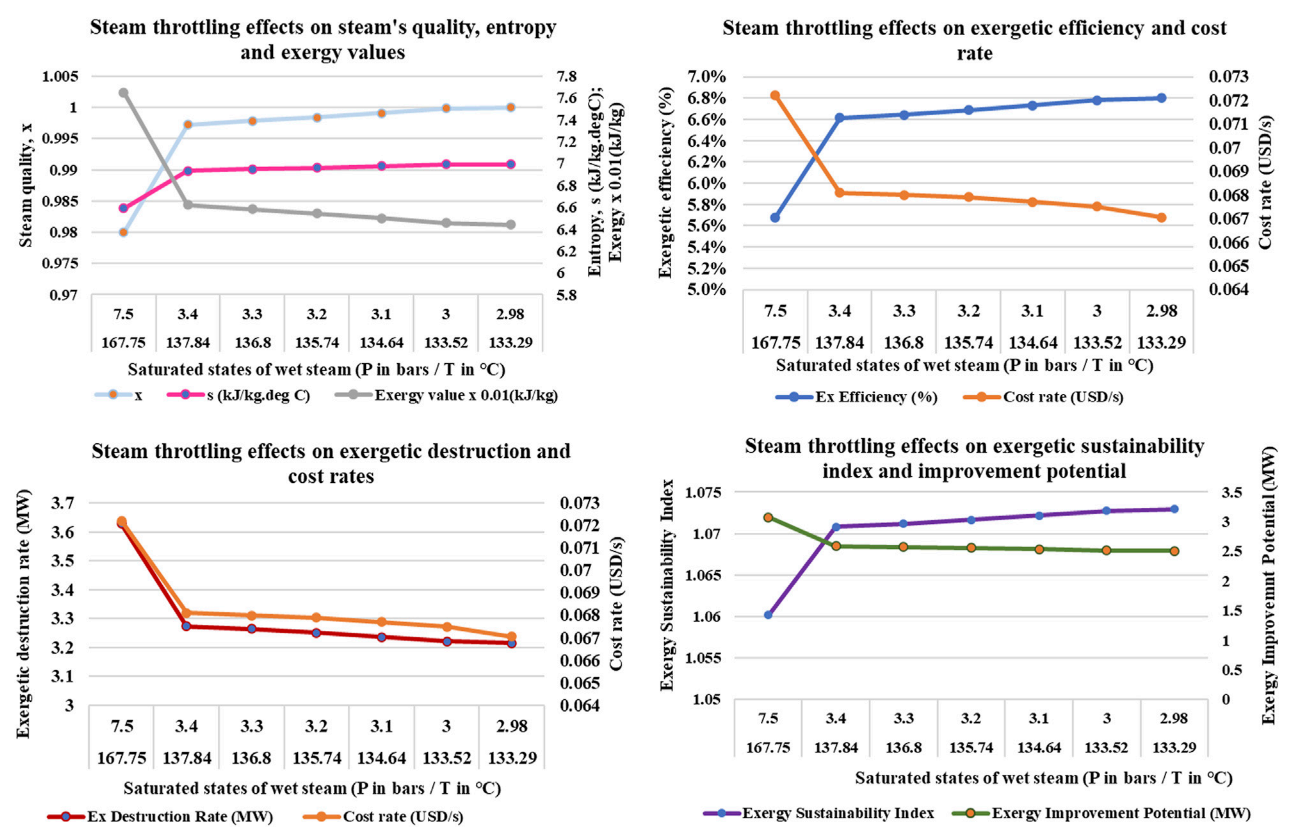

FIGURE 6
Effects of steam throttling on exergetic performance variables and cost rate for wort processing system.

dominance of exergy destruction cost rate during the processing of the malted grist. To improve efficiency and reduce fuel costs, it is important to decrease exergy destruction during malted grist processing. One potential solution is to lower mass flow rates of hot water and malt grist while keeping exergetic product value constant.

Overall, the low values of f_k for the processes confirm that the cost associated with processing the grist into premashed products was primarily dominated by exergy destruction.

3.3.2 Exergoeconomic performance indicators for components of the brewhouse

Table 7 also presents the exergoeconomic variables for each component in the brewhouse. The wort kettle, the whirlpool and the mash filter, in decreasing order, were pinpointed as the most significant components from an exergoeconomic standpoint. The wort kettle had the greatest impact on the brewhouse's cost rate. Its exergoeconomic factor, Figure 3, reveals that the costs related to the wort kettle were mostly dominated by the exergy destruction cost rate. Hence, improving the kettle's performance can reduce the cost of wort produced per hectoliter. To reduce exergy destruction, steam heating at low temperature, thermal cladding of kettle, and eliminating the preboiling phase are improvement potentials. Implementing these measures can increase the non-exergetic cost rate $\dot{Z}_k$ of the wort kettle, but it can improve the overall cost-effectiveness of the brewhouse.

The second most relevant component, the whirlpool, has a low f_k value and a relatively low r_k value - a precursor that the cost rate of the product stream from the component was largely dominated by the cost rate of exergy destruction associated with the component.

Therefore, it is expected that the cost-effectiveness of the wort production would improve if the whirlpool's cost rate of exergy destruction is minimized even at the expense of increased $\dot{Z}_k$ for the component. Also, as deduced from the exergetic studies of the brewhouse, the pumps are center of attention due to their low exergetic efficiencies. Pumps AKP, HVP, MTP, WKP, and WLP were found to have exergoeconomic factors that were higher for typical pumps ($f_k > 70$ as defined by Bejan et al., 1996), Figure 4. Conclusively their low-cost effectiveness was largely due to their capital and O&M cost rates $\dot{Z}_k$ values.

Hence, less efficient or smaller pumps will improve the overall cost-effectiveness of the wort processes. Unlike the remaining pumps in the section, the Whirlpool Transfer Pump, WLP, showed a remarkable and relatively low f_k value. Therefore, a reduction in its avoidable exergy destruction rate should improve the cost effectiveness of the production section.

The preheater had a very low f_k value which indicates a largely dominated exergy destruction cost rate. To reduce this rate and drop the chilled wort cost rate, it is recommendable to investigate the thermodynamic properties related to the Very Hot Water (VHW) such as the inlet temperature, pressure, and mass flow rate. It is safer to consider measures related to the VHW properties rather than adjusting the wort properties which may alter the biochemistry of the wort and the performances of downstream components. Based on the exergetic destruction rate model for the preheater, a reduction of 30% in the mass flow rate of the VHW stream decreases the component's destruction rate to 0.1399 MW accompanied with approximately 6% reduction in the cost rate of the preheater main product. However, an exergetic splitting of the component's destruction rate into its avoidable and unavoidable components will reveal to what extent the preheater's destruction rate can be minimized.

3.3.3 Relative performances of the wort system components and sections

Credible optimization efforts involving numerous components can result in practical benefits such as reduced energy consumption, minimized material usage, and lowered costs.

Figure 5 highlights the relative performances of all the components based on the tripod analyses conducted. From an energy analysis standpoint, the wort kettle, preheater, premasher, mash tun, and mash filter were identified as the top five significant components in decreasing order of energy consumption. From the exergy analysis standpoint, the wort kettle (42.7911%), mash tun (10.8086%), preheater (10.0683%), whirlpool (8.3522%), and adjunct kettle (6.2705%) were identified as the top five components with the highest rates of total exergy destruction. And from the exergoeconomic analysis, the wort kettle, whirlpool, mash filter, mash tun, and adjunct kettle were pinpointed as the top five most significant components in decreasing order with overall relative total cost increases of 46.7896%, 18.8689%, 11.9940%, 7.8957%, and 3.7985% respectively. This ranking outperforms that generated from exergetic analysis because it resulted from the combined studies of exergetic performance and economic viability for each component in the production line. The quality of the results from the exergoeconomic analyses is enhanced when evaluated values of non-exergetic cost rates are replaced with current prices supplied by equipment vendors.

In conclusion, the tripod analyses of the wort production have identified the wort kettle as the top priority component for optimization efforts. Improving the steam heating process conditions for the wort kettle, mash tun, and adjunct kettle, which are all connected to the same fuel stream, is expected to increase their thermodynamic efficiencies, decrease the total exergy destruction rate, and lower the cost rate of the wort produced. Other optimization potentials worth investigating for the wort processes include reduction in the mass flowrate of the very hot water supplied to the preheater and minimization of investment costs while optimizing volumetric flow rates and efficiencies of pumps for mash and wort transfers.

More importantly, the results of this research showed that the average energy intensity values for wort production, both electrical and thermal, were comparable to values reported for European breweries by Scheller et al. (2008), 0.84 kwh/hL and 10.2 kwh/hL, respectively. However, the presence of adjunct maize in the brewing ingredients (19.40% of the total brewing grains) resulted in noticeable variations in the values reported due to changes in the specific heat capacity and density of the mash produced. Additionally, other factors such as the age of brewing equipment, climatic differences, and adopted steam heating pressure in breweries, may have influenced the results. Further correlations between the findings of this research and reported literature on the three main wort production processes (mashing, heating, and wort boiling) are observable in Slawitsch et al. (2014) and Scheller et al. (2008). Slawitsch et al. (2014) developed a brewery model to evaluate the thermal load in brewing processes. The model was based on energy audits in various international breweries, representing 80%–90% of real brewery energy usage. The results from the model for three selected breweries of different sizes for mashing, heating, and wort boiling were as follows: 5.39–5.87 MJ/hL (Decoction) for mashing, 6.83–9.88 MJ/hL for heating, and 2.19–7.88 MJ/hL for wort boiling. These results aligned well with the values obtained from this research: mashing (6.38 MJ/hL, Decoction), heating (9.38 MJ/hL), and wort boiling (17.50 MJ/hL, 5% total evaporation). The variation in wort boiling values could be attributed to energy losses on brewing lines and the purity of brewing grains. The results also correlated well with the findings of Scheller et al. (2008) for European breweries: mashing (7.96 MJ/hL), heating (11.84 MJ/hL), and wort boiling (4.5% total evaporation) (10.87 MJ/hL). The study also observed an expected increase in thermal load for a 5%–4.5% total evaporation for wort stripping.

In comparison to dairy milk systems, the wort production system is less energy efficient. Oztuna (2023) found that a dairy milk system with fifteen operational components had an overall energy efficiency of 45.5%, while Yildrim and Genc (2017) reported an overall efficiency of 85.4% for milk powder production from whole milk using eight operational components. The lower energy efficiency of the wort production system can be attributed to its nineteen operational components, which create more sources of inefficiency.

The efficiency of a system is impacted by entropy production or exergetic destruction, which increases costs for O&M and other operating parameters. Similar production lines for processed materials might have a similar trend of exergoeconomic total cost increase ($\dot{C}_{D,k} + \dot{Z}_k$), except for differences in equipment age and climatic conditions. Exergoeconomic studies of wort beer production line have not been reported in open literature, to the best of the authors' knowledge, therefore treatment of these present findings was limited to findings in other beverage production lines, at both exergetic level and exergoeconomic levels. In the exergetic investigation of a malt drink production line (65% malted barley, 20% sorghum, and 15% maize) as reported in Fadare et al. (2010), cumulative entropy production and specific exergy destruction for the malt's wort production were reported as 15,636.20 MJ and 27.82 MJ/hL, respectively. With a cumulative exergy destruction of 15,894.68 MJ and a specific exergy destruction of 27.91 MJ/hL found in this present work, a very high correlation exists in the specific exergetic destruction for a high gravity wort for beer production and standard gravity wort for malt drink production. However, as found in this research, the wort kettle (42.79%) borne the highest destruction of the total supply exergy ahead of the mash tun (10.81%) while in the malt drink plant, the mash tun (33.64%) borne the highest destruction ahead of the wort kettle (30.06%). In the exergetic study of red wine production, Genc et al. (2017) estimated the cumulative exergy loss for red wine processes as 2,692.51 kW for 1 kg/s of grape processed within twelve operational components. The pneumatic press had the highest exergy destruction evaluated at 2003 kW. Hence, the cumulative exergy loss for high-gravity wort production in an industrial-scaled facility is relatively higher. In Tinoco-Caicedo et al. (2020), the operational cost rate for instant coffee production was estimated at 207.90 USD/h, with an operational exergetic efficiency of 33%. When compared to the 245.41 USD/h obtained from this study, it is evident that the cost rate for wort production is relatively higher than that of instant coffee production for the evaluated exergetic efficiency.

3.4 Optimization potentials of key exergetic indicators using steam throttling mechanism

The analysis of the steam distribution conditions used in the heating process of brewing in the visited Anheuser-Busch InBev breweries in Nigeria suggests potential for improvement in energy efficiency and cost reduction of processed brews. By implementing steam throttling to just before the superheat conditions, optimization opportunities can be realized. The process of steam throttling results in a pressure drop leading to an increase in steam quality and a drop in temperature. Through adjustment of the wet steam pressure within its saturated region, notable effects on exergetic performance indicators were observed for the studied brewery, Figure 6. Specifically, at a throttled down value of 2.98 bars, the wet steam was found to approach its dry vapor state, representing the lowest throttled condition for wet steam at the predefined heating content, enthalpic value of 2,724.49 kJ/kg. Nevertheless, adjusting the steam heating pressure from 3.4 bars to 3.0 bars resulted in an enhancement of the exergetic efficiency of the wort production system, with an increase from 6.61% to 6.78%. This adjustment led to a notable 1.60% reduction in exergetic destruction and a decrease in cost rates from 0.0681 USD/s to 0.0675 USD/s. These positive changes can be attributed to the lower exergy value of the wet steam, which now possesses a higher dryness fraction and low temperature at the desired enthalpic value. However, the exergetic improvement potential changes from 2.5861 MW to 2.5140 MW with a corresponding change from 1.0708 to 1.0727 for the exergetic sustainability index. The analysis underscores the influence of pressure reduction via steam throttling on the exergoeconomic performance of the wort processing system, particularly in terms of fuel cost and the size of process heating brewing components. Notably, implementing steam throttling along the wort production line presents an annual cost-saving opportunity of USD 17,280.

4 Conclusion

This study analyzed the energy quality in the wort production of an industrial-scale brewery and identified the components that impact the performance of the process from energy, exergy and exergoeconomics standpoints. The energetic analyses showed that the energy requirements per hectoliter of high-gravity wort were estimated at (86 ± 1) MJ/hL with an operational energy efficiency of 30.35%. The top five significant components were identified as the wort kettle, preheater, premasher, mash tun, and mash filter. The exergetic analyses revealed that the overall exergetic destruction rate and specific destruction rate for the wort production were 3.2737 MW and 9.4348 k W/hL, respectively, at an operational exergetic efficiency of 6.61%. The overall improvement potential and sustainability index were estimated at 2.5861 MW and 1.0708, respectively. Additionally, the top five components with the highest rates of cumulative exergy destruction were the wort kettle (42.7911%), mash tun (10.8086%), preheater (10.0683%), whirlpool (8.3522%), and adjunct kettle (6.2705). Lastly, the exergoeconomic analyses revealed a cost rate of 0.0681 USD/s for wort production and pinpointed the most significant components as the wort kettle, whirlpool, mash filter, mash tun, and adjunct kettle. Further studies could focus on quantifying the cost savings accruable to the optimization potentials identified in the wort production.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

OS: Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Writing–original draft, Writing–review and editing. TS: Data curation, Formal Analysis, Investigation, Methodology, Software, Supervision, Validation, Writing–original draft, Writing–review and editing. OO: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Supervision, Validation, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2024.1456688/full#supplementary-material

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Nomenclatures

$\dot{C}$	Cost rate (USD/s)
$\dot{E}x$	Exergy rate, kW
CI	Capital Investment
ex	Specific exergy, kJ/kg
h	Specific enthalpy, kJ
hl	hectoliter
°P	Degree Plato
PEC	Purchase Equipment Cost
s	Specific entropy, kJ/K
S	Salvage value
$\dot{W}$	Work rate, kW
x	Mass fraction
X	Dryness fraction
$\dot{m}$	Mass flow rate, kg/s
$\dot{Z}$	Component cost rate in United States Dollar per second, USD/s

Subscripts

0	Reference conditions
D	Destruction
e	Exit properties of stream
F	Fuel
i	Inlet properties of stream
k	Component k
o	Outlet of a component
Q	Heat energy
tot	Total
W	Electrical energy input

Superscripts

e	Electrical energy
h	Human energy
k	Component

Greek Letters

ϴ	Maintenance factor
ϑ	Specific volume
φ_{II}	Exergetic efficiency
Ƞ	First Law Energy efficiency
ρ	Density
δ	Uncertainty
Ø	Thermal efficiency of section
φ_k	Thermal efficiency of component