SVU-International Journal of Engineering Sciences and Applications (2024) 5(2): 43-49
Print ISSN 2785-9967| Online ISSN 2735-4571
DOI 10.21608/svusrc.2024.251812.1165

Energy and exergy analysis of a sugar cane factory in Egypt

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Abstract: The current paper presents an energetic and exergetic of the Edfu sugarcane factory in Egypt. The major purpose of the present implementation is to separately analyze the major components of the cogeneration system for the sugar cane factory and to find and quantify the components with the highest energy losses and exergetic destruction. In the present study, exergy methods with traditional energy analysis are used to assess the thermodynamic efficiencies and losses. Based on the actual data of operating the factory, the results show that the system achieves an overall energy efficiency and an exergy efficiency of 75.17% and 36.85%, respectively. The maximum energy loss occurs in the juice heating process (JHP) at 66128.25 kW, followed by the boiler at 32499.4 kW. In addition, the maximum exergy destruction occurs in the power boiler at a rate of 130926.9 kW, so the boiler contributes 83% of the overall exergy destruction in the cogeneration system.

Keywords: Energy; Exergy; Cogeneration system; Sugar cane factory.

1 Introduction

Creating cultured sugar from raw sugarcane juice requires a number of physical procedures, which are part of Egypt's main agricultural industry [1]. The sugarcane industry in Egypt dates back to 710 AD [2]. All Egyptian sugarcane factories are self-sufficient in energy, such as thermal and electrical, because a waste product of the juice extraction process called bagasse is used as a primary fuel in the boilers [3]. In the sugar industry, the cogeneration system is used to produce electrical and thermal energies.

Combined power and heat, also known as combined heat and power (CHP), uses a power plant to produce multiple forms of energy from a singular fuel resource. In recent years, cogeneration systems have become a popular technology used in many industrial and residential applications to generate power and heat. In the sugar industry, a cogeneration plant is typically used to initially generate power and then electricity for various process heat applications such as drying, centrifuges, process heaters, etc. Cogeneration is a thermodynamically efficient system that uses fuels. With the individual generation of electricity, part of the energy must be disposed of as waste heat, while with the combination of heat and power, this wasted thermal energy is reused. All thermal power plants dissipate thermal energy when generating electrical energy, which can be transferred to the surrounding environment using cooling towers, exhaust gases, or other means. Due to its advantages compared to other simple systems, cogeneration is recognized by various governments as an interesting tool to curb the energy crisis.

The fundamental components of the sugar factory are the boiler, steam turbine, and heaters for the juice process. The boiler is the most essential element because it is the main energy converter, converting water to superheated steam and extracting heat from the gases burning inside the furnace [4]. Sugar mills often use steam turbines to drive the mills, which convert the thermal energy into mechanical energy. On the other hand, the steam turbines employed in sugar mills are usually impulse single-stage turbines with an efficiency in the range of 25-30% [5]. Juice heaters utilized in sugar mills consist of a series of tubes in which the juice flows, and the steam circulating outside heats up the juice. Using the cogeneration systems in sugar factories could improve the exergy and energy

Received: 28 November 2023/ Accepted: 13 January 2024
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efficiency of the factory. There are numerous scientific papers published based on the energy and exergy analysis of the cogeneration systems in the sugar industry.

Aljundi [6] performed an exergetic analysis of the Al-Hussein 396 MW power plant located in Jordan. The efficiency of the power plant was evaluated through the modeling of different components. As well, a detailed study of energy and exergy losses for the power plant was presented. It was found that 77% of the total exergetic destruction was in the boiler. Kamate and Gangavati [7] studied an exergetic analysis of a cogeneration power plant for the sugar industry in India using bagasse as boiler fuel. The results showed that the boiler was the critical component that contributed to the overall inefficiency of the system due to its inherent nature. In addition, increasing the temperature and pressure of the steam generation reduced the exergy losses and improved the exergy efficiency.

Moreover, Hector et al. [8] investigated the energy and exergetic analysis of Colombian sugar factories producing sugar and ethanol from sugarcane. They revealed that the cogeneration system accounted for more than 70% of the sugar mills thermodynamic inefficiencies. Ghiasirad et al. [9] analyzed the experimental data from the Urmia sugar beet factory in Iran. They demonstrated that the cogeneration parts had the minimum exergy efficiency of 20.17%, while the overall exergy efficiency of the power plant was 56.44%.

Kamate and Gangavati [10] performed energy and exergy analyses of a 44 MW cogeneration system in Belgaum, India, using bagasse as the boiler fuel. The results showed that the major energy losses were in the condenser and boiler at 27 MW and 35 MW, respectively. As well, the highest exergy destruction that occurred in the boiler was 71%. In addition, the overall exergy efficiency of the system was 25%. Saidur et al. [11] conducted energy and exergy analyses of a boiler employing methane (CH_4) as the main fuel in Malaysia. The result showed that the energy and exergy efficiencies of the boiler were 72.46% and 24.89%, respectively. Ayyagari [12] estimated the energy and exergy efficiencies of a boiler in a power plant-based coal in India. Under the design conditions, the energy and exergy efficiencies of the boiler were 85.54% and 41.81%, respectively. Whereas at 80% and 60% off design cases, the energy efficiency improved to 85.77% and 85.71%, respectively. The exergy efficiency at 80% and 60% of a design condition was 41.64% and 41.59%, respectively.

Parvez and Hasan [13] accomplished energy and exergy analyses of a sugarcane boiler in India, using bagasse as the main fuel in the boiler. The result showed that the boiler's energy and exergy efficiencies were 81.78 and 25.08%, respectively. Additionally, the boiler's exergy destruction was 45.56%, followed by the heat exchangers with 17.23%. Chantasiriwan [14] minimized the exergy destruction by integrating a steam dryer into the cogeneration system to minimize the moisture content of bagasse before combustion in the sugarcane industry in Thailand. The results showed that the energy efficiency of the cogeneration increased by 5% more than that without a steam dryer under the same operating conditions as the sugar juice processing.

The above literature review shows that studying energy and exergy analysis has drawn more attention from designers and scientists. In the present implementation, energy and exergy analyses of a cogeneration system for the sugar cane factory are proposed and investigated. The current research attempts to provide useful information on energy losses, exergy destruction, thermal efficiency, and exergy efficiency for the core cogeneration system components used by the sugar sector.

2 Process description

Figure 1 shows the systematic layout of the CHP plant in the Edfu sugar cane factory. The system's fundamental components are the boiler, steam turbine, juice heating process, condensate pump, de-aerator (D), and feed water pump. Bagasse produced from the juice extraction system with a moisture content of 50% by weight is used as a fuel in the boilers that produce steam at a temperature of 350 °C and a pressure of 25 bar. The steam generated in the boiler is fed to the turbine. The operating principle of the steam turbine is based on the expansion of steam within the turbine. Superheated steam under high pressure is generated in the energy boilers, which produce mechanical energy through expansion in the steam turbine, and it is used in a generator to produce electricity.

A back-pressure steam turbine used in the cogeneration power plant in the Edfu sugar factory expands the superheated steam from the inlet state at a pressure of 25 bar and 350 °C to generate exhaust steam at the outlet at a pressure of 2.5 bar and 150 °C to generate electricity, which is consumed in the sugar production processes. After that, the back-pressure steam from the turbine is de-superheated in the superheating process to satisfy the thermal requirements in juice heating processes. Cooling water is added in the de-superheating process to convert the superheated steam into saturated steam. Hot condensate water from the sugar juice heating processes is sent to the de-aerator at state point 13. The required make-up water is supplied to the de-aerator at point 14. The condensate water outlet of the de-aerator is maintained at a temperature of 105 °C and stored at atmospheric pressure in a storage feed water tank. Thus, the feed water is provided to the boiler using the feed water pump at state point 1. The temperature, pressure, and mass flow rate at different points of the system of the sugar cane factory are listed in Table 1.

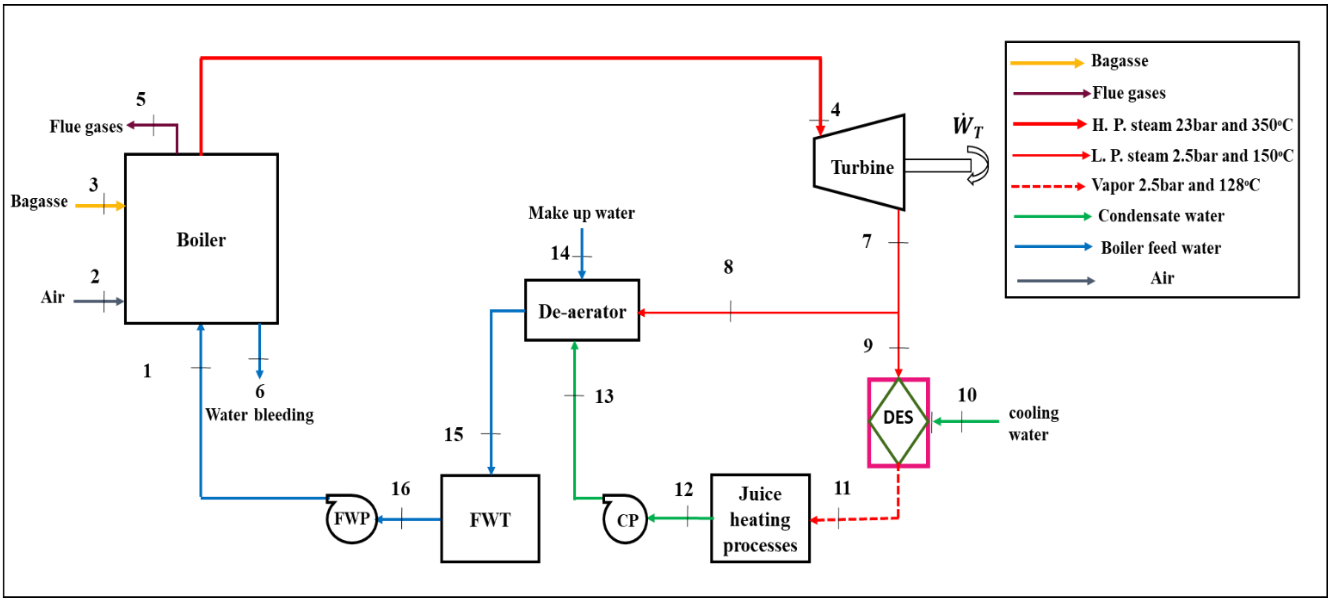

Fig. 1. General layout of the cogeneration thermal power plant of Edfu sugar factory.

Table 1
Thermodynamic operating properties at each point.

Point	Substance	$\dot{m}$ (kg/s)	T (°C)	p (bar)	h (kJ/kg)	s (kJ/kg.K)
1	Feed water	35.5	97	35	409.03	1.2704
2	Combustion air	65	25	1.02	----	----
3	Bagasse	17	30	----	7650	----
4	High pressure steam	34.5	350	25	3127	6.8424
5	Flue gases	81	160	--	121.4	----
6	Water bleeding	1	220	25	943.69	2.5175
7	Exhaust steam	34.5	150	2.5	2765.2	7.1707
8	Exhaust steam	6.5	150	2.5	2765.2	7.1707
9	Exhaust steam	28	150	2.5	2765.2	7.1707
10	Cooling water	0.25	100	2.5	419.21	1.3069
11	Vapor	28.25	128	2.50	2717.8	7.0556
12	Condensate water	28.25	90	1.01	376.99	1.1926
13	Condensate water	28.25	90	2.50	377.11	1.1925
14	Make up water	3.5	25	2.50	105.07	0.36719
15	Condensate water	38.25	105	2.50	440.31	1.3631
16	Condensate water	35.5	97	1.01	406.45	1.273

3 Energy and exergy analysis

Thermodynamics plays a fundamental role in conducting the energy and exergy analysis of the cogeneration system. Exergy analysis-based the first and second laws of thermodynamics is an important approach for the energy analysis. The exergy can be employed to identify the location and magnitude of the exergy destruction; it also reveals inefficient thermodynamics. To create the thermodynamic model, the following assumptions are taken into consideration:

1. The cogeneration system works in a steady-state.
2. The changes in kinetic and potential energies of each component are neglected.
3. Each element of the cogeneration system is regarded as a control volume and an open steady-state thermodynamic system.
4. The water properties are identified using steam tables.
5. The chemical exergy of bagasse is considered for evaluating the overall exergy efficiency.
6. The physical exergies of flue gases and steam/water flows are employed to assess the exergy losses in the boiler.
7. The conditions of the reference or dead point of temperature and pressure are 25 °C and 1.01325 bars, respectively.
8. The principles of ideal gas are assumed to apply to air and combustion products.

The thermodynamic modeling of the cogeneration system is based on the principles of mass, energy and exergy balance principles, respectively [15].

3.1 Energy analysis

For a steady-state process, the mass balance for each component is given as:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

where $\dot{m}$ indicates the mass flow rate of the working fluid; suffix 'in' and 'out' indicate the inlet and outlet conditions, respectively.
The first law of thermodynamics presents the energy balance for any open system as follows [16]:

$$\sum \dot{Q}_{cv} - \dot{W}_{cv} = \sum \dot{m}_{out}\left(h_{out} + \frac{V^2{}_{out}}{2} + gZ_{out}\right) - \sum \dot{m}_{in}\left(h_{in} + \frac{V^2{}_{in}}{2} + gZ_{in}\right) \tag{2}$$

where $\dot{Q}_{cv}$ is the heat transfer to or from the operating system, $\dot{W}_{cv}$ is the net power generated by or upon the system, h is the specific enthalpy, V is the bulk velocity of the working fluid, g is the acceleration due to gravity force, and Z is the height above the sea level.
The energy efficiency of each process can be defined as the ratio between the energy produce to the energy consumed in the process [17], and it is calculated as follows:

$$\eta_{en} = \frac{\text{Desired output energy}}{\text{Input energy}} = 1 - \frac{\text{Energy loss}}{\text{Input energy}} = 1 - \frac{\dot{En}_{loss}}{\sum \dot{En}_{in}} \tag{3}$$

where η_{en} introduces the energy efficiency for each component in the processes of the sugar production.
The η_{en} can be defined as the ratio between the total enthalpy at the system outlet to the total enthalpy at the system input.
The net energy transferred to a system is the difference between the input energy and the output energy:

$$\dot{En}_{loss} = \sum \dot{En}_{in} - \sum \dot{En}_{out} \tag{4}$$

The enthalpy of bagasse or lower heating value (LHV) is calculated by the correlation given by [18]. The specific energy for air and combustion gases with constant specific heats can be calculated using the following relation [19]:

$$en_{air/fg} = h_T - h_0 = C_{p(T)}T - C_{p(T_0)}T_0 \tag{5}$$

The air enthalpy can be evaluated from the ideal gas properties of air tables [20].

3.2 Exergy analysis

The general exergy balance for a specified control volume is given by:

$$\sum \dot{Q}_{cv}\left[1 - \frac{T_0}{T_i}\right] - \dot{W}_{cv} + \sum \dot{m}_{in} * ex_{in} - \sum \dot{m}_{out} * ex_{out} = \sum \dot{EX}_{dest} \tag{6}$$

where ex is the specific exergy of the components, and is given by [21]:

$$ex = (h - h_0) - T_0(s - s_0) \tag{7}$$

The equations for the specific exergy inflow and the specific exergy production, respectively, of a stationary open thermodynamic system are:

$$ex_{in} = (h_{in} - h_0) - T_0(s_{in} - s_o) \tag{8}$$

$$ex_{out} = (h_{out} - h_0) - T_0(s_{out} - s_o) \tag{9}$$

where h_o, s_o, and T_o are the enthalpy, entropy, and temperature in the reference state, respectively.
The total exergy rate can be estimated as follows:

$$\dot{Ex} = \dot{m} * ex \tag{10}$$

Using these equations, the exergy destruction rate or the exergy destruction can be defined as [17]:

$$\sum \dot{Ex}_{dest} = \sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} \tag{11}$$

The exergy efficiency of the processes is presented by the following equation [22]:

$$\eta_{ex} = \frac{Exergy\ output}{Exergy\ input} = 1 - \frac{\sum \dot{Ex}_{des}}{\sum \dot{Ex}_{in}} \tag{12}$$

The specific exergies for air and exhaust gas with constant specific heat is determined by [23]:

$$ex_{a,fg} = c_{air,fg}\left[(T - T_o) - T_o \ln\left(\frac{T}{T_o}\right)\right] + RT_o \ln\left(\frac{p}{p_o}\right) \tag{13}$$

where R is the universal gas constant, p is the pressure in bar, and $c_{air,fg}$ is the specific heat for air and exhaust gas in kJ/kg.K.

The specific heat capacity of air is a function of absolute temperature expressed as [24]:

$$C_{air} = 1.04841 - \frac{3.8379T}{10^4} + \frac{9.45378T^2}{10^7} - \frac{5.49031T^3}{10^{10}} + \frac{7.92981\,T^4}{10^{14}} \tag{14}$$

where the temperature is given in K.
The specific heat of flue combustion gases that arise from the combustion of bagasse in a boiler is given by [18]:

$$C_{fg} = \left(0.27 + 0.00006T_{fg}\right) \quad (15)$$

where T is the temperature in °C; C_{fg} is the specific heat in kJ/kg.K.

The lower heating value (LHV) or the net calorific value (NCV) of the bagasse is calculated using Hugo's correlation [18]. A bagasse with a moisture content of 50% and a soluble solids content of 1.96% is assumed. Based on the dry matter, the following bagasse composition is assumed: 47% of carbon (C), 6.5% of hydrogen (H), 44% of oxygen (O), and 2.5% of ash. To determine the exergy of bagasse, Eq. (16) is used [23]:

$$Q_{dry} = \frac{1.0438 + 0.1882\left[\frac{h}{c}\right] - 0.2509\left[1 + 0.7256\frac{h}{c}\right] + 0.0383\left[\frac{n}{c}\right]}{1 - 0.3035\left[\frac{o}{c}\right]} \quad (16)$$

The notations h, c, n, and o represent the mass fractions of hydrogen, carbon, nitrogen, and oxygen, respectively. However, in the sugar industry, wet bagasse with a moisture content of 50% is burned in the boilers. Considering the fuel moisture, the chemical exergy for wet bagasse is estimated by the following formula [23]:

$$\pounds_{o} = \left[NCV + wh_{fg}\right]Q_{dry} + 9417s \quad (17)$$

where w is the mass fraction of fuel moisture, which is assumed to be 0.5 for bagasse. The NCV or LHV of the fuel is 7650 kJ/kg [18], and for water substance at T_o= 298.15 K, h_{fg} = 2442 kJ/kg, and s is the sulfur content in the fuel (bagasse). But the sulfur content in the fuel is zero because it is an organic fuel. Therefore, the chemical exergy for bagasse equals:

$$\pounds_{o} = [7650 + 0.5 * 2442]Q_{dry} \quad (18)$$

3.2.1 Exergy analysis of the boiler

Exergy balance for the boiler according to Eqn. (11) is expressed by the formula:

$$\dot{Ex}_{dest,\text{Boiler}} = \dot{Ex}_1 + \dot{Ex}_2 + \dot{Ex}_3 - \dot{Ex}_4 - \dot{Ex}_5 - \dot{Ex}_6 \quad (19)$$

The exergy efficiency for the boiler according to Eqn. (12) is defined as:

$$\eta_{ex,\text{Boiler}} = 1 - \frac{\dot{Ex}_{\boldsymbol{dest}}}{\sum \dot{Ex}_{\boldsymbol{in}}} = 1 - \frac{\dot{Ex}_{dest,\text{Boiler}}}{\dot{Ex}_1 + \dot{Ex}_2 + \dot{Ex}_3} \quad (20)$$

3.2.2 Exergy analysis of the turbine

Exergy balance for the turbine according to Eqn. (11) is obtained by:

$$\dot{Ex}_{dest,\text{Turbine}} = \dot{Ex}_4 - \dot{Ex}_7 - \dot{W}_{elc} \quad (21)$$

Exergy efficiency for the turbine according to Eqn. (12) is defined as:

$$\eta_{ex,\text{Turbine}} = 1 - \frac{\dot{Ex}_{\boldsymbol{dest}}}{\sum \dot{Ex}_{\boldsymbol{in}}} = 1 - \frac{\dot{Ex}_{dest,\text{Turbine}}}{\dot{Ex}_4} \quad (22)$$

3.2.3 Exergy analysis for juice heating processes (JHP)

The exergy balance for the JHP according to Eqn. (11) is expressed by:

$$\dot{Ex}_{dest,\text{JHP}} = \dot{Ex}_{11} - \dot{Ex}_{12} \quad (23)$$

The exergy efficiency for the JHP according to Eqn. (12) is defined as:

$$\eta_{ex,\text{JHP}} = 1 - \frac{\dot{Ex}_{\boldsymbol{dest}}}{\sum \dot{Ex}_{\boldsymbol{in}}} = 1 - \frac{\dot{Ex}_{dest\,,\text{JHP}}}{\dot{Ex}_{11}} \quad (24)$$

3.2.4 Exergy analysis of the de-aerator (D)

The exergy balance for the de-aerator according to Eqn. (11) is given by:

$$\dot{Ex}_{dest,\text{D}} = \dot{Ex}_8 + \dot{Ex}_{13} + \dot{Ex}_{14} - \dot{Ex}_{15} \quad (25)$$

The exergy efficiency for the de-aerator according to Eqn. (12) is estimated by:

$$\eta_{ex,\text{D}} = 1 - \frac{\dot{Ex}_{\boldsymbol{dest}}}{\sum \dot{Ex}_{\boldsymbol{in}}} = 1 - \frac{\dot{Ex}_{dest,\text{D}}}{\dot{Ex}_8 + \dot{Ex}_{13} + \dot{Ex}_{14}} \quad (26)$$

4 Results and discussion

Table 2 illustrates the rates of energy losses and exergy destruction for the main elements in the system for the sugar cane factory. The results show that the highest energy loss occurs in JHP at 66128.25 kW, this is due to the energy losses in the condensate water during the process. The second component that has high energy loss is the boiler, with 32499.4 kW, since the most thermal energy is lost through the exhaust gases. Therefore, not all of the heat generated by the combustion of the fuel can be transformed into the water or steam present in the boiler. In addition, it can be found that the energy losses of the de-aerator and turbine are 12153.05 kW and 2482.1 kW, respectively. On the other hand, the maximum exergy destruction rate is presented in the boiler and then in the JHP at a rate of 130926.9 kW and 16770.7 kW, respectively. Moreover, the following elements that have high exergy destruction are the turbine and de-aerator, with 5857.4 kW and 3378.7 kW, respectively.

Figure 2 shows the percentage of energy losses for the main elements of the system. The results indicate that the percentages of energy losses in JHP and boiler are 57.71% and 28.36%, respectively. While the energy loss percentages for the remaining components represent 14% of the overall energy losses in the system.

Figure 3 shows the percentage ratio between the exergy destruction and the total exergy destruction for each element of the cogeneration system. It is found that the boiler's exergy destruction accounts 83% of the total exergy destruction in the cogeneration system. Therefore, the boiler is the main source of irreversibility in the boiler which the rate of exergy destruction and the exergetic efficiency are 130926.9 kW and 22.70%, respectively. The highest irreversibility is especially as a result of the heat transfer to the working fluid and the losses in the exhaust gases. The second component with a high exergy destruction is the JHP, which generates 11% of the total exergy destruction in the system at a rate of 16770.7 kW. The JHP produces a large amount of exergetic destruction due to the energy transferred under large temperature differences, water condensation temperatures, and inefficiency in the fermentation process. The percentages of exergy destruction for the remaining components represent 6.33% of the total exergy destruction.

Figure 4 shows the energy and exergy efficiencies for each element of the cogeneration system. It is found that the energy efficiency for the boiler, turbine, de-aerator**,** and JHP is estimated at 77.52%, 97.7%, 13.87, and 58%, respectively. In addition, it is observed that the exergy efficiency of the turbine equals 84.46%. Furthermore, the minimum exergy efficiency is obtained for JHP at 4.21%, which is 22.7% for the boiler and 30.42% for the de-aerator.

Table 2
Energy losses, exergy destruction, energy efficiency and exergy efficiency for the main components in the cogeneration system.

Components	Energy losses rate (kW)	Exergy destruction rate (kW)
Boiler	32499.4	130926.9
Turbine	2482.1	5857.35
JHP	66128.25	16770.68
De-aerator	12153.05	3378.65
Overall	**113262.8**	**156933.6**

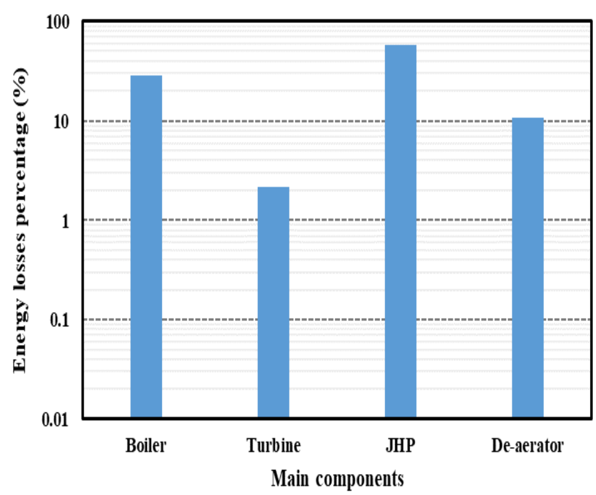

Fig. 2. Percentage of energy losses for the main components of the system.

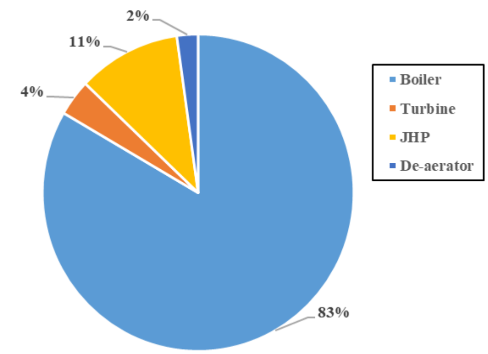

Fig. 3. Exergy destruction percentage for the main components of the system.

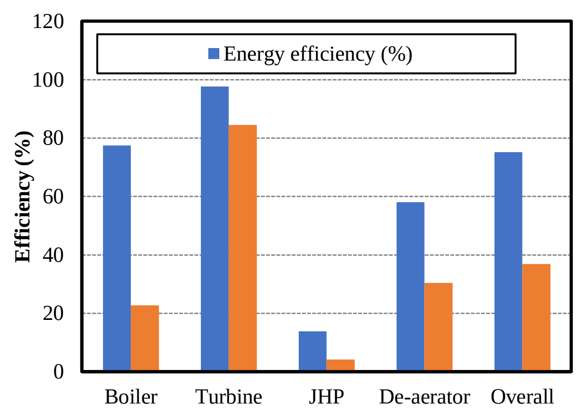

Fig. 4. Energy and exergy efficiencies for the main components and the system.

5 Conclusions

The current study introduces an energy and exergy analysis of the cogeneration system of the Edfu sugar cane factory using actual data from operating the factory. The main aim of this work is to analyze comprehensively and separately the system components to identify and quantify the sites with considerable energy and exergy losses during actual operation. Exergy efficiency provides a more sensitive understanding of performance than energy efficiency. The main conclusions that can be drawn from this study are:

- JHP loses the most energy at 66128.25 kW, followed by the boiler at 32499.4 kW.
- The boiler, turbine, and system as a whole achieve energy thermal efficiencies of 77.52%, 97.69%, and 75.17%, respectively.
- The exergy efficiency for the boiler, turbine, and whole system equals 22.70%, 84.46%, and 36.85%, respectively.
- The maximum exergetic destruction and its percentage are in boilers and JHP at 131 MW with a percentage of 83% and 16.8 MW with a percentage of 11%, respectively.

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Nomenclature	
C	Specific heat, (kJ/kg.K)
$en_{air/fg}$	Specific energy for air and combustion gases, (kJ/kg)
ex	Specific exergy, (kJ/kg)
E	Energy rate, (kW)
$\dot{E}x$	Exergy rate, (kW)
h	Specific enthalpy, (kJ/kg)
$\dot{m}$	Mass flow rate, (kg/s)
p	Pressure, (bar)
Q_{dry}	Ratio of chemical exergy to net calorific value of fuel
$\dot{Q}$	Heat transfer rate, (kW)
R	Universal gas constant, (kJ/kg.K)
s	Specific entropy, (kJ/kg.K)
T	Temperature, (K)
V	Velocity, (m/s)
$\dot{W}$	Net power, (kW)
$\dot{W}_t$	Net power generated from turbine, (kW)
Z	Altitude relative to the sea level, (m)
Greek symbols	
η_{en}	Energy efficiency, (%)
η_{ex}	Exergy efficiency, (%)
$£_{o}$	Chemical exergy of fuel, (kJ/kg)
ω	Moisture content on bagasse, (kg/kg)
Subscripts	
o	reference state
air	air
atm	Atmospheric
des	destruction
elc	electric
fg	flow gas
in	inflow
L	loss
out	outflow
Acronyms	
CHP	Condensate heat pump
D	De-aerator
FWT	Feed water tank
JHP	Juice heating processes
LHV	Lower heating value, (kJ/kg)
NCV	Net calorific value, (kJ/kg)