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Energy Efficiency Improvement Approaches in a Sugarcane Industry: A Case Study

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Abstract

Sugarcane processing industry is believed to consume a high amount of energy through several production stages. Consequently, the cost of energy is considered an important item in total production costs that consuming a detectable part of the company's annual profits. Energy audit program (EAP) is considered an important pillar to mitigate the high-cost production for improving the efficiency of industrial operating conditions. It improves the efficiency of the factory's components through three scenarios. The first is starting from classifying the utilities inputs and outputs to evaluate energy balance of each equipment. Results indicated that in the first scenario by using steam dairator, the fuel flow rate can be reduced by 189.49 m^3/h which raise the energy efficiency by 6.32 %. In the second scenario, boiler blowdown heat exchanger only, flow rate of 166 m^3/h of fuel can be saved with 5.52 % increasing in energy efficiency. In the third scenario, mixing between the two previous scenarios will increase the energy efficiency by 22.1 % via saving fuel reached about 664 m^3/h. It was found that the suggestive solutions are significantly contributed remarkable improving in the company's energy efficiency. Consequently, they decrease energy cost items and increase the company's annual output profits.

Keywords: Energy Recovery; Efficiency improvement; Fuel Saving; Industrial Boiler.

1. Introduction

Recently, it was a powerful trend in rising the human populations coupled with a climatic changing that forced the world to provide more energy and saving the environment away from climate changing [1,2]. Sugarcane is a worthwhile cash crop used as a raw material in a lot of food industries, especially in sugar processes industry. The average global yield of sugarcane was approximately 70 ton per hectare during 2021 which represented nearly 80% of global sugar production [3,4]. The sugar factories are classified from medium to large scales with a complex energy integration of the process for providing the high production. Generally, it is well known that energy is considered one of the important factors in the sugarcane facilities. These industrial production processes in such factories are ranging between medium to large scales working with very complex energy integrating system that supported the high yield production [5,6]. In sugarcane factories, two types of energies have been utilized; the Thermal Energy (T.E) and electric power. The T.E is considered the highest energy consumption for fulfilling the requirements of the production process that contributed by the higher share in the operational costs. Production process started by heating the sugarcane juice with steam that usually produced from evaporation station. Rocha et al (2022), showed that the heat was indirectly transferred through shell and tube exchanger unit because it has a large heat transfer area [7]. Energy conservation can be implied as smart and efficient use of source to confirm that a particular maximum amount of energy activity, productive work and profitability has been achieved. In order to achieve higher annual production profits; energy cost has to be minimized by applying a

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proper Energy Audit Program EAP [8]. The EAP is a technique for identifying energy losses, quantifying them, estimating conservation potential, evolving technological options for conservation and evaluating techno-economics for the measure suggested as stated by Ndugi et al (2015) [9]. There are several alternatives to increase the boiler efficiency; such as: (i) lowering the stack temperature, (ii) preheating the combustion air, (iii) recovery heat from boiler blowdown, (iv) cooling the blowdown and heat up the makeup water, (v) reducing the steam usage by insulating the piping, tanks and others utilities that heated by steam [10-12]. Scientists concerned studies on improving the boiler house efficiency and provided several recommendations that resulted net increase of 2% in the overall boiler efficiency and in some cases, it reached to 15 % [13, 14].

The current article presents a case study that performed EAP for a sugarcane industrial company located in Egypt. The thermal and electric energies have been identified through detailed classification of each energy utilization. It aims also, to find out the actual situations of energy needs and utilization in a steam demand process with needed electrical energy. Identification, evaluation, and analysis of the steam flow in the used boiler for the production process have been detailed studied.

2. Materials and Methods

The current study performed an EAP to present the energy efficiency improving approaches in both thermal energy and electric power utilized in the sugarcane company industrial plant. Three scenarios have been proposed in the current study. The first scenario is to preheat the feed water side prior entering the boiler via a steam dairator only; the second is to preheat the feed water with steam from boiler blowdown, and the third scenario is a mixture between both first and second scenarios. The study studied the scenarios implementation at variable flow rates and percentages of steam dairator with boiler blowdown. It also focused on the recommended 6% ratio of steam dairator and boiler blowdown.

2.1 Thermal Energy Data Collection

2.1.1 Distillation Plant

The distillation plant contains two water tube boilers which produces 20 and 25 ton/h steam from the first and second boilers; respectively. A balance between water and steam has been made for the quantities of the boiler. A collected data of consumed daily quantities of fuel, the exhaust resulting from burning the fuel, and the resulting steam are represented as flow rates. Temperature, operating pressure, as well as the boiler blowing rate, are shown in Fig. (1).

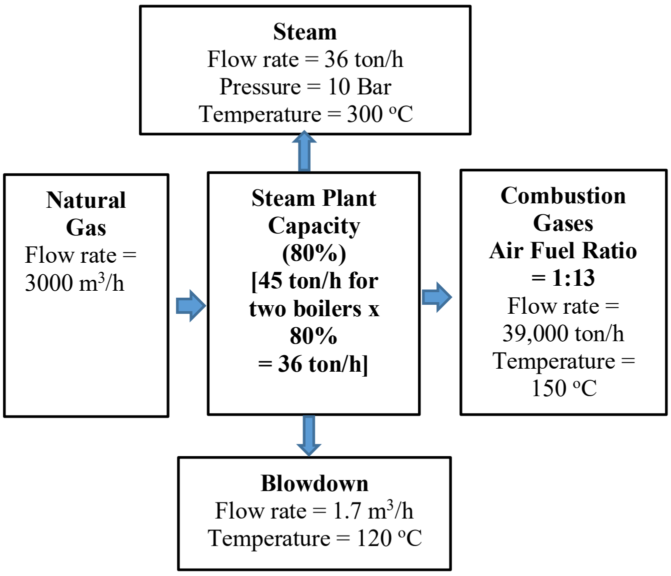

Fig. 1 Mass Balance of Distillation Plant Boiler

2.1.2 Chemical plant

The chemical plant contained one water tube boiler with 25 tons steam per hour. A balance of water and steam for the boiler has been made for the quantities as shown in Fig. (2). The daily quantities of fuel consumed and the resulting exhaust from fuel burning, and the resulting steam are shown as flow rate, temperature, and operating pressure, as well as the boiler blowing rate.

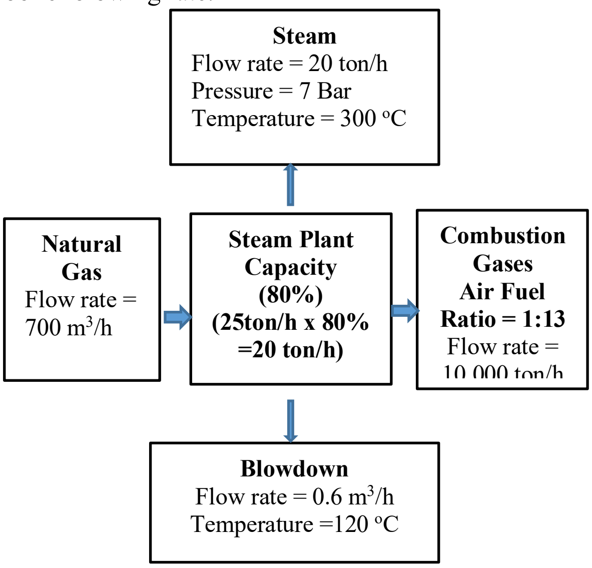

Fig. 2 Mass Balance of Chemical Plant Boiler

2.1.3 Improvement of Thermal Energy Efficiency

Based on the actual collected data of thermal and electric energy consumptions at the sugarcane plants; energy audits are conducted to evaluate the efficiency of the equipment process system and all processes that use energy. The EAP included all the energy sources that operating the facility. It includes: (i) identify the energy flow for each fuel used, (ii) quantify the energy flow into separate functions, (iii) evaluating the efficiency of each function, (iv) identifying energy and cost savings opportunities. A detailed analyses of energy consumption and losses have been carried out after identifying the equipment's that consumed major energy rates. All the possible methods to improve the boiler efficiency and to achieve maximum benefits from the energy recovery system to minimize the heat losses are presented in Fig. (3) as one of the typical industrial boilers from the previous studied cases in sugarcane companies. This study is mainly focused on the preheating of feed water prior passing to the boiler via a steam dairator and boiler blowdown energies. A boiler energy balance is studied in case of using specific steam dairator, blowdown energy, both steam dairator and blowdown energies; respectively.

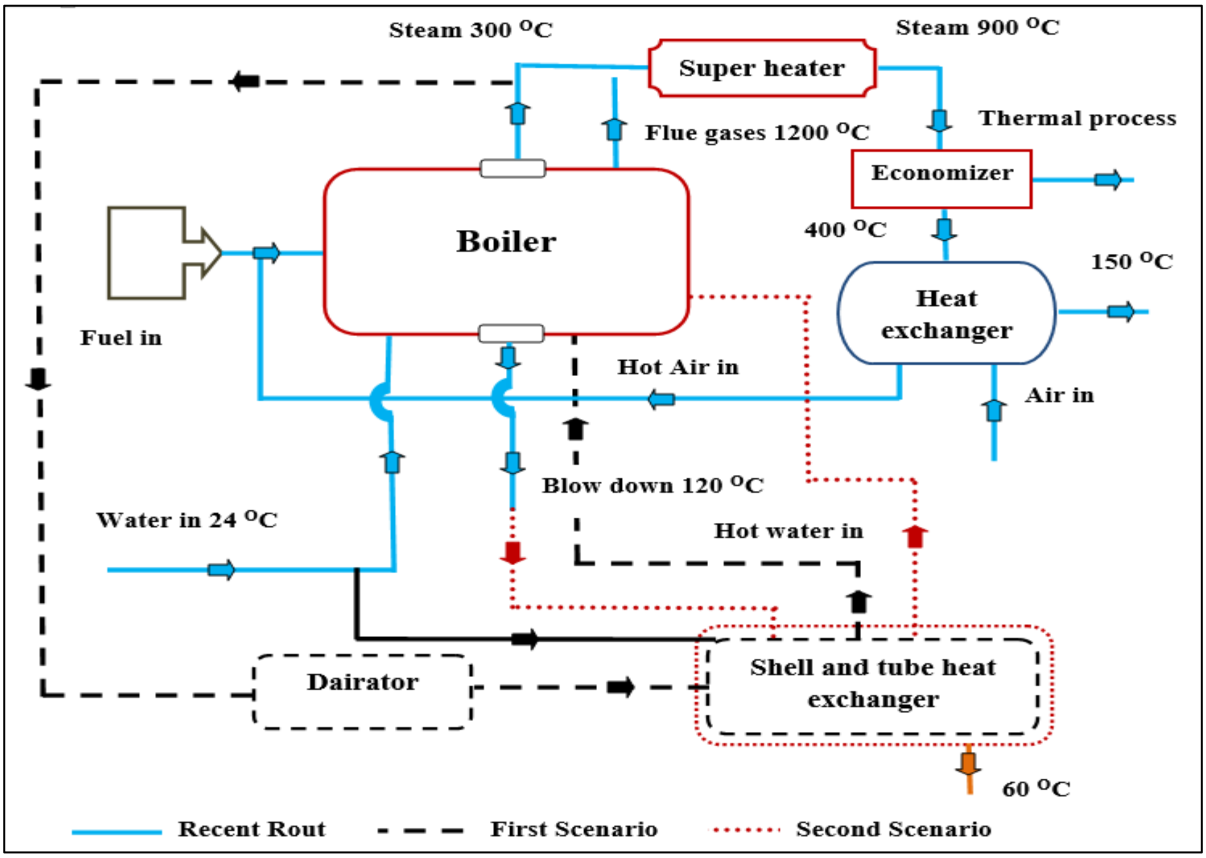

Fig. 3 Energy balance of the distillation plant of industrial boiler with proposed scenarios

Making energy balance of the steam dairator, the feed water temperature can be estimated as per the following equations:

$$m_{sd}\ h_g = (m_{fwi} + m_{sd})C_{pw}\,(T_{fwo} - T_{fwi}) \quad (1)$$

$$m_{sd}\ h_g + (m_{fwi} + m_{sd})C_{pw}\,(T_{fwi}) = (m_{fwi} + m_{sd})C_{pw}\,(T_{fwo}) \quad (2)$$

$$T_{fwo} = T_{fwi} + \frac{m_{sd}\ h_g}{(m_{fwi}+m_{sd})C_{pw}} \quad (3)$$

Making energy balance of the steam blowdown heat exchanger, the feed water temperature can be estimated as per the following equations:

$$m_{bdi}\ (h_{bdi} - h_{bdo}) = (m_{fwi})C_{pw}\,(T_{fwo} - T_{fwi}) \quad (4)$$

$$T_{fwo} = T_{fwi} + \frac{m_{bdi}\ (h_{bdi}-h_{bdo})}{(m_{fwi})C_{pw}} \quad (5)$$

2.2 Electric Energy Data Collection

All the consumed electricity by different sections in the company were estimated to be 164 MWh 24 MWh (about 15.7%) is consumed by the wastewater treatment plant and the other consumed electricity distribute as shown in the next tables.

Table 1. Distribution of consumed electricity in different operation sections of distillation plant

Location	Consumed power (MW)	Percentage
Distillation unit	0.84	13 %
Vinegar	0.98	15.4%
Acetic Acid	0.252	3.9%
CO_2	0.14	2.2%
Dryers	0.056	0.86%
Vinas	0.084	1.3%
Boilers	0.392	6%
Luminescent	0.056	0.86%
All consumed power	**2.8**	

Table 2. Distribution of consumed electricity in different operation sections of the chemical plant

Location	Consumed power (MW)	Percentage
Fresh yeast	1.45	22.4 %
Dry yeast	0.20	3%
Sulfates	0.20	3%
Oxygen	0.15	2.3%
Alcohol	0.15	2.3%
Distillation & esterification	0.10	1.5%
Adhesives	0.05	0.7%
Luminescent	0.05	0.7%
Central workshop	0.084	1.3%
All consumed power	**2.55**	

2.3 Electricity produced by solar energy

Based on the daily solar radiation average of about 6 $kWh/m^2/day$ and on-grid photovoltaic solar system the size [15] of the PV system in Wp for the peak load of energy can be defined as mentioned [16,17]:

$$APV = \frac{EL}{H \times \eta PV \times \eta_{inv} \times T_c} \quad (6)$$

Considering, the photovoltaic efficiency $\eta PV = 0.20$, the inverter efficiency = 0.90, the temperature correction factor = 0.90, the photovoltaic modules area was estimated as 185 m^2. The power of the photovoltaic modules can be estimated using the following equation

$$P_{pv} = A_{PV} \times Hsc \times \eta_{PV} \quad (7)$$

Where,

A_{pv} = total area of photovoltaic requirement (m^2).

H = daily global irradiation ($Wh/m^2/d$).

Hsc = Standard solar irradiation, 1,000 W/m^2.

The total available area which can be used to install PV system was estimated to be 9000 m^2.

3- Results and Discussion

3-1 Thermal Energy Efficiency Improvement

3.1 .1 Effect of using steam dairator only

The study has been carried out using several steam dairator with mixing ratios starting from 0.0% i.e., without using steam dairator, up to 10.0 % with increment of 1.0 %. Consequently, eleven calculation runs are made for several steam dairator with the same 1:10 mixing ratios. The following parameters were estimated; feed water outlet temperature, steam dairator flow rates, thermal energy feeding the steam dairator, percentage of energy saving, percentage of efficiency improving, amount of fuel saving, and percentage of fuel saving; respectively. The temperature's variation of feeding water outlets and dairator steam flow rates values comparable at different percentage of dairator steam flow rates is shown in Fig. 4. It was found also that as the percentage of dairator steam flow rates increased, the feed water outlet temperature was increased due to increasing the inlet steam thermal energy to the steam dairator. Consequently, it was clear also that as the percentage of dairator steam flow rates increased, the estimated values of the dairator steam flow rates were increased too. Moreover, the variation of steam dairator thermal energy input, kW and feed water flow rates values with different percentage of dairator steam flow rates is shown in Fig. 5. It was found that as the percentage of dairator steam flow rates increased, the feed water flow rates were also decreased. It is clear also that as the percentage of dairator steam flow rates increased, the thermal energy input, kW is increased.
A remarkable finding is shown in Fig. 6, where the recommended percentage of dairator steam flow rates is about 6%. At this percentage; the feed water outlet temperature, the dairator steam flow rate, steam

dairator thermal energy input, and feed water flow rate was estimated as 63°C, 0.56 kg/s, 1550 kW, 8.84 kg/s, respectively.

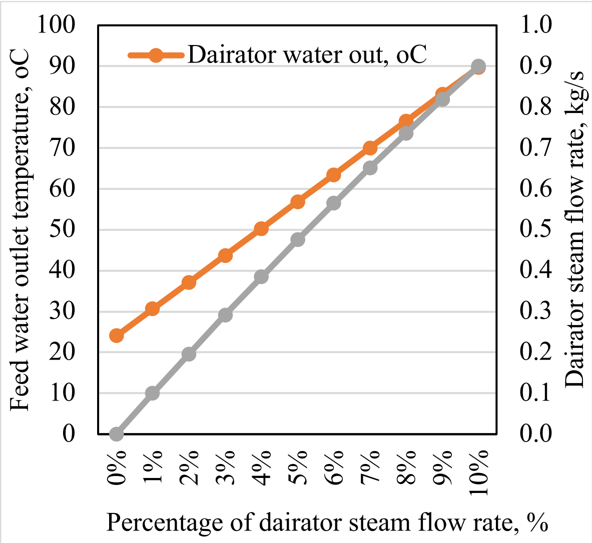

Fig. 4 Variation of feed water outlet temperature and dairator steam flow rates values with different percentages of dairator steam flow rates

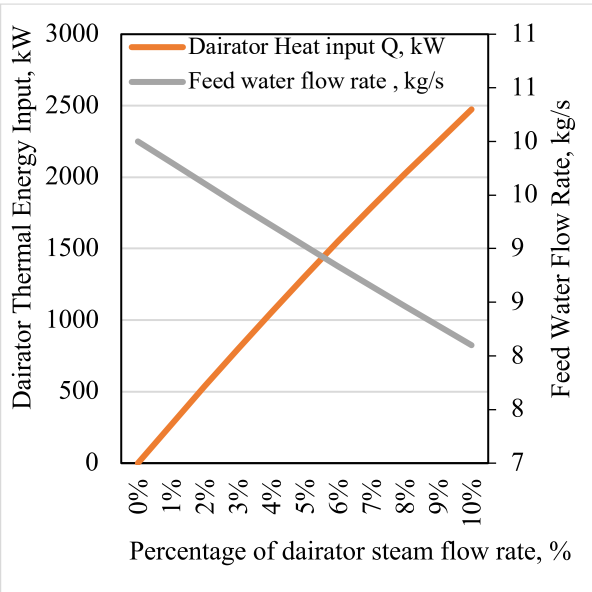

Fig. 5 Variation of steam dairator thermal energy input, kW and feed water flow rates values with different percentages of dairator steam flow rates

The amount of fuel saving flow rates with different percentages of dairator steam flow rates is represented in Fig. 6. It was found that as the amount of fuel saving flow rates increased with increasing the percentages of the dairator steam flow rates. At the percentage of dairator steam flow rates equals to 6%, an amount of fuel saving flow rate of 189.49 m^3/h was achieved.

Figure 6 shows the variation in the percentage of fuel saving with different percentages of dairator steam flow rates.

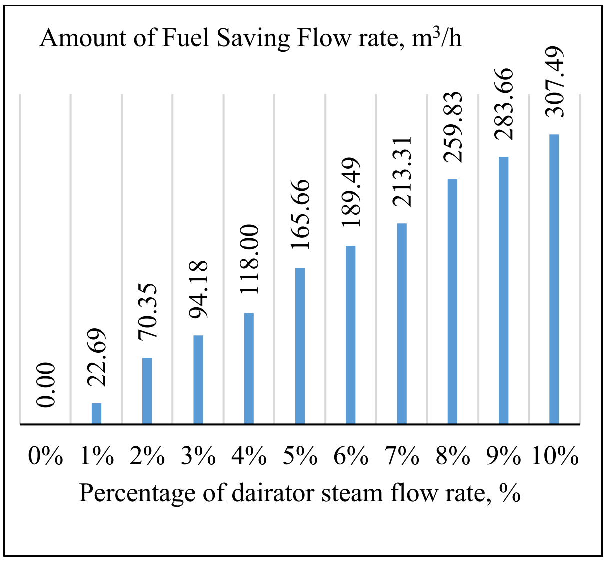

Fig. 6 Amount of fuel saving flow rates with different percentages of dairator steam flow rates

It is found that the percentage of fuel saving increased with increasing the percentages of the dairator steam flow rates. At the percentage of dairator steam flow rates equal to 6%, an amount of fuel saving flow rate of 6.32 % is achieved.

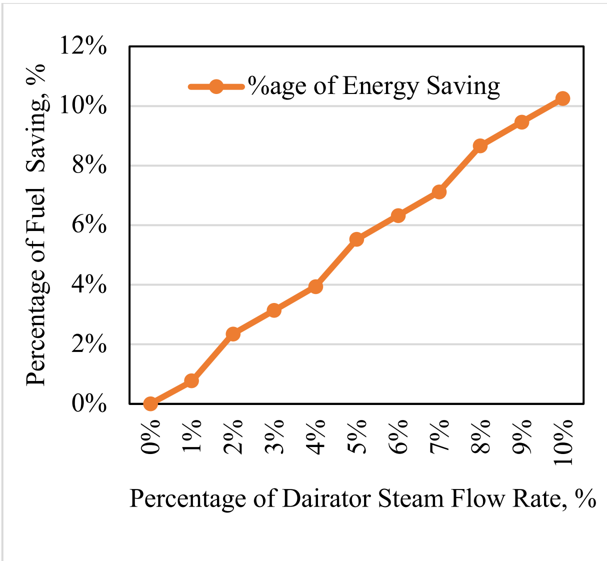

Fig. 7 Variation in fuel percentage saving with different percentage of dairator steam flow rates

The variation of the percentage of efficiency improvement with different percentages of dairator steam flow rates is shown in Fig. 8. It was found that the percentage of efficiency improvement increased with increasing the percentages of the dairator steam flow rates. At the percentage of dairator steam flow rates equal to 6%, an amount of efficiency improvement of 5.1 % is achieved.

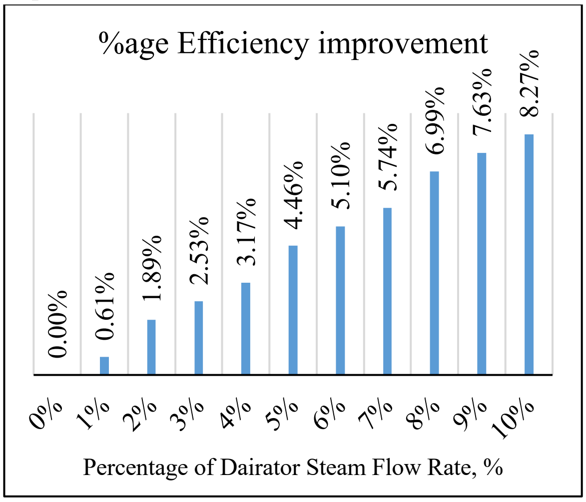

Fig. 8 Variation of the improvement percentage efficiency with different percentage of dairator steam flow rates

3.1.2 Effect of using boiler blowdown heat exchanger only

The study has been carried out at several steam blow-down with mixing ratios starting from 0.0 to 10.0 % with increment of 1%. Eleven calculation runs have been carried out at several steam blowdown heat exchanger at mixing ratios 0.0:10.0 %. The following parameters are estimated; the feed water outlet temperature, steam blowdown heat exchanger flow rates, thermal energy feeding the steam blowdown heat exchanger, the percentage of energy saving, the percentage of efficiency improving, amount of fuel saving, and percentage of fuel saving, respectively. The variation of feed water outlet temperature and blowdown flow rates values with different percentages of boiler blowdown is shown in Fig. 9. It was found that as the percentage of boiler blowdown increased, the feed water outlet temperature is increased due to increasing the inlet blowdown thermal energy to the heat exchanger. It is cleared also that as the percentage of boiler blowdown increased, the estimated values of the blowdown flow rates is increased. At the percentage of blowdown equal to 6%, the feed water outlet temperature, the blowdown flow rate was estimated as 59ºC, 0.56 kg/s respectively. These results agree with a lot of obtained results which indicated that, most of energy losses occurs in boiler and energy loses can be minimized by using the steam blowdown [18,19]. The variation of the percentage of energy saving with different percentages of blowdown flow rates as shown in Fig. 10. It was found that the percentage of energy saving increased with increasing the percentages of the blowdown flow rates. At the percentage of blowdown flow rate equal 6%, the percentage of energy saving of 5.52%, is achieved.

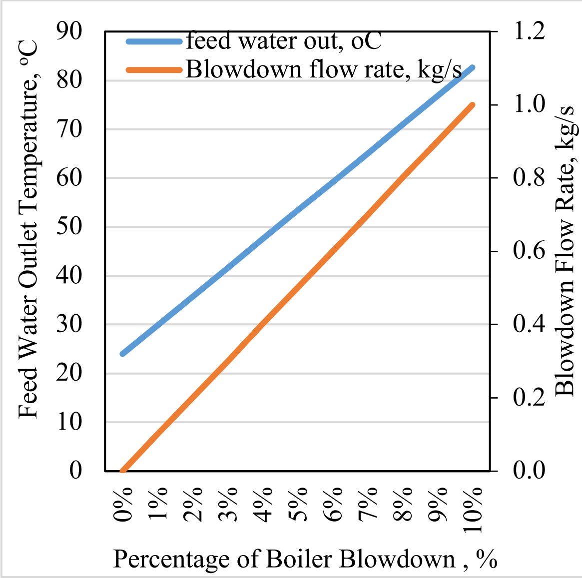

Fig. 9 Variation of feed water outlet temperature and blowdown flow rates values with different percentages of percentage of boiler blowdown

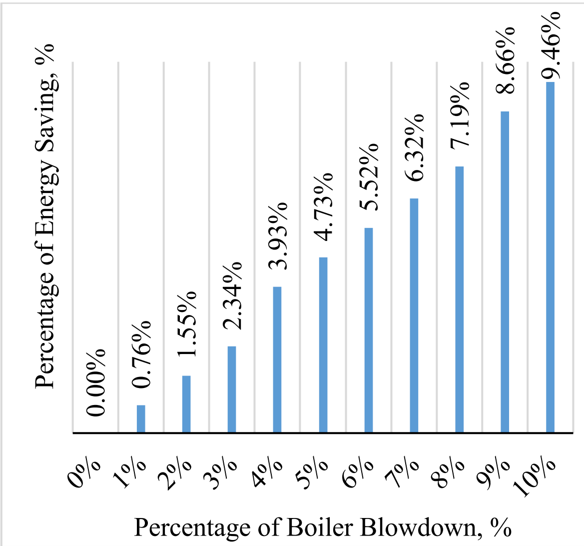

Fig. 10 Variation of the percentage of energy saving with different percentages of blowdown flow rates

The amount of fuel flow rates and fuel saving percentage with different percentages of blowdown flow rates is shown in Fig. (11). It was found that as the percentages of blowdown increased, the amount of fuel flow rates was decreased and the percentage of fuel saving is increased. At the percentage of blowdown equal 6%, the fuel flow rate is estimated as 2834 m^3/h which means saving and amount of 166 m^3/h from the ordinary fuel flow rate (3000 m^3/h) which is corresponding to 5.52 % fuel saving.

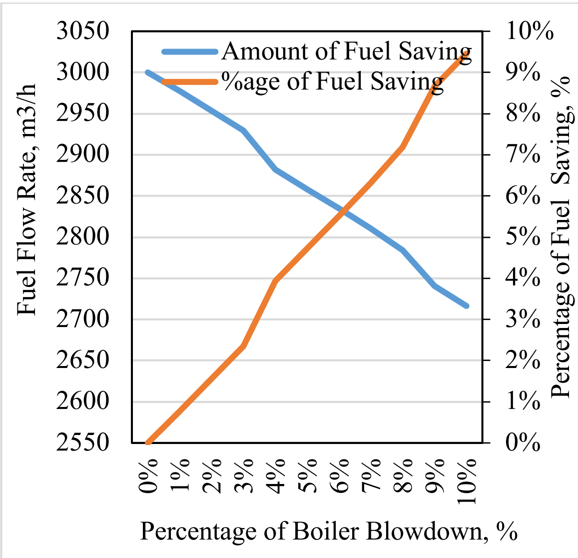

Fig. 11 Amount of fuel flow rates and fuel saving percentage with different percentages of blowdown flow rates

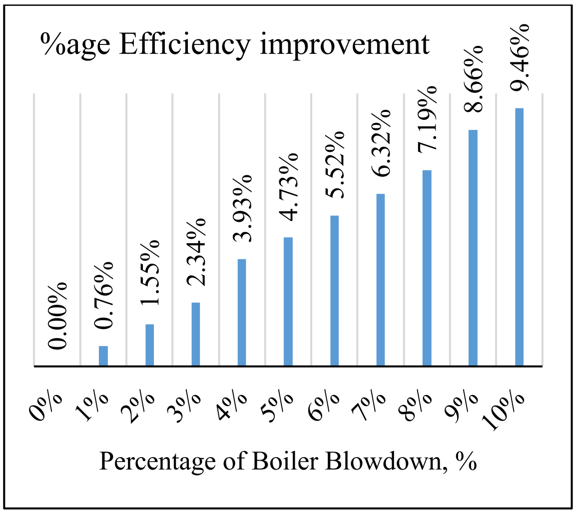

Fig. 12 Variation of the percentage of efficiency improvement with different percentages of blowdown flow rates

The variation of the percentage of efficiency improvement with different percentages of blowdown flow rates is shown in Fig. (13). It is found that the percentage of efficiency improvement increased with increasing the percentages of the blowdown flow rates. At the percentage of blowdown flow rates equal to 6%, an amount of efficiency improvement of 5.52 % is achieved

3.1.3 Effect of using Boiler blowdown heat exchanger and steam dairator

The third scenario is to study the effect of using several percentages of blowdown heat exchanger and steam dairator flow rates from 0% (without using steam blowdown and dairator) to 10 % with increment of 1%. The energy balance of the boiler, steam dairator and steam blowdown is shown in Fig. (13).

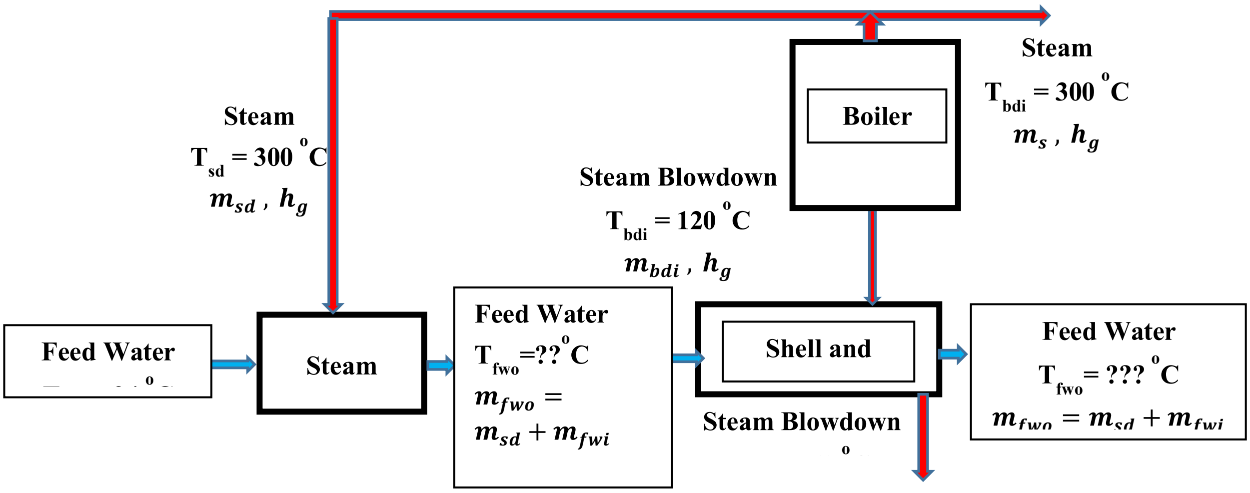

Fig. 13 Energy balance of the steam blowdown heat exchanger

Making energy balance of the steam blowdown heat exchanger and steam dairator, the feed water temperature estimated in equation (3) is considered as an input feed water temperature in equation (5), then the outlet feed water temperature of utilizing steam dairator and blowdown heat exchanger is estimated as shown in Fig. 14.

It is cleared that the feed water outlet temperatures from steam dairator and blowdown heat exchanger are increased with increasing the percentage of steam dairator and blowdown heat exchanger. At the percentage of steam dairator and blowdown heat exchanger flow rates equal to 6%, the feed water outlet temperature from steam dairator estimated as 63 ºC and when it is entered to the heat exchanger, the output value of 99 ºC was achieved.

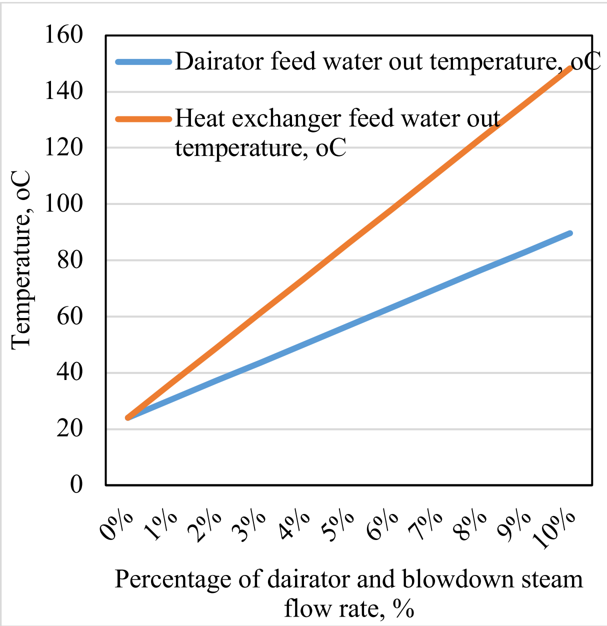

Fig. 14 Variation of feed water outlet temperatures from steam dairator and blowdown heat exchanger

The variation of percentage of energy saving of using steam dairator and blowdown heat exchanger flow rates is shown in Fig. (16) It was found that the percentage of energy saving increased with increasing the percentages of steam dairator and blowdown heat exchanger flow rates. At the percentage of steam dairator and blowdown heat exchanger flow rates equal 6%, the percentage of energy saving of 22.13%, is achieved.

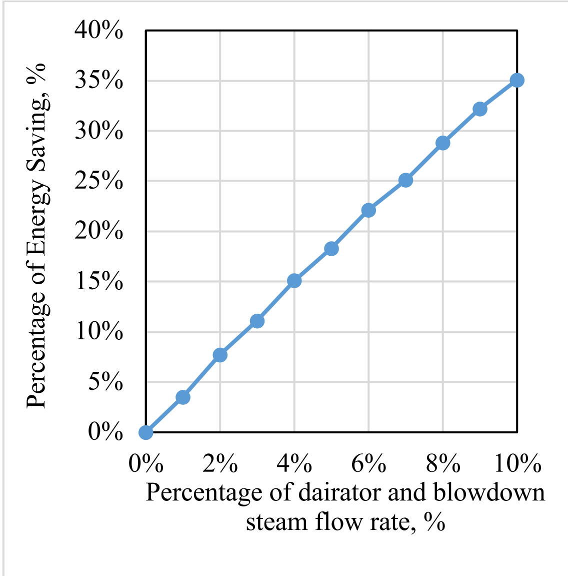

Fig. 15 Variation of percentage of energy saving of using steam dairator and blowdown heat exchanger

The amount of fuel flow rates saving with different percentages of steam dairator and blowdown heat exchanger flow rates is shown in Fig. 17. It is found that the as the percentages of steam dairator and blowdown heat exchanger flow rates increased, the amount of fuel flow rates is decreased. At the percentage of steam dairator and blowdown heat exchanger flow rates equal 6%, the fuel flow rate is estimated as 664 m^3/h which corresponding to 22.13 % fuel saving.

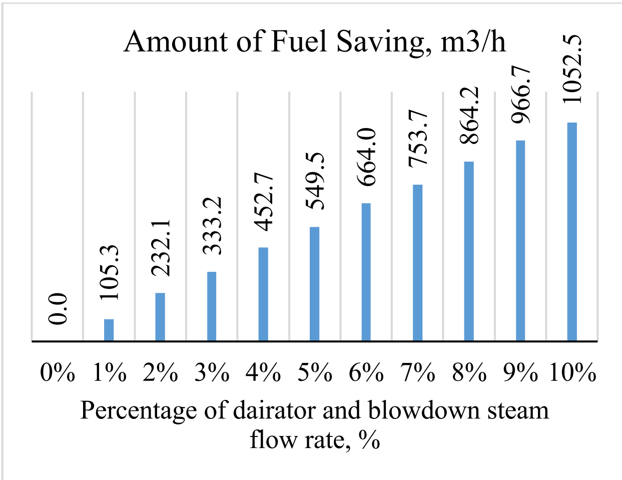

Fig. 17 Amount of fuel flow rates saving with different percentages of steam dairator and blowdown heat exchanger flow rates

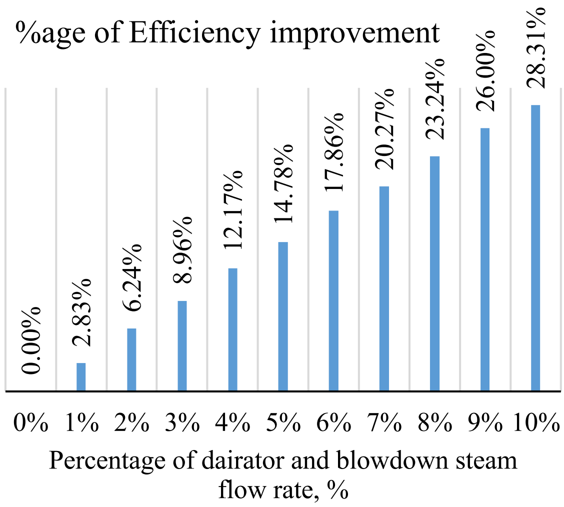

Fig. 18 Variation of the percentage of efficiency improvement with different percentages of steam dairator and blowdown heat exchanger flow rates

The variation of the percentage of efficiency improvement with different percentages of steam dairator and blowdown heat exchanger flow rates is shown in Fig. (18) It was found that the percentage of efficiency improvement increased with increasing the percentages of the steam dairator and blowdown heat exchanger flow rates. At the percentage of blowdown flow rates equal to 6%, an amount of efficiency improvement of 17.86 % is achieved

3.2 Electric Energy Saving

It is found that the total building's roof sunny area equal to 9000 m^2. The estimated area can be utilized by installing on-grid photovoltaic solar system to produce electricity that connected to the national grid as shown in figure (19)

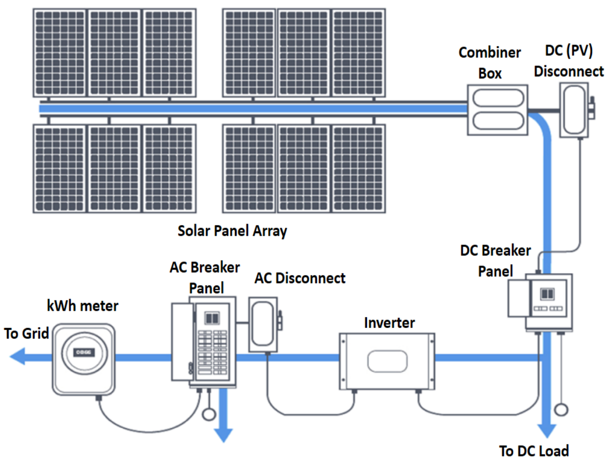

Fig. 19 On-grid PV solar energy system

4. Conclusion

Energy efficiency improving is considered one of the most important parameters to efficiently working the industrial boilers. Among the several parameters that improve the boiler efficiency. The current study is focused only in the preheating the feed water side prior entering the boiler via a steam dairator and boiler blowdown energies. The study implemented using several flow rates percentages of the steam dairator and boiler blowdown and focused one the recommended 6% ratio of steam dairator and boiler blowdown. Some concluded remarks can be listed below: -

1- Effect of using steam dairator only

- the feed water outlet temperature, the dairator steam flow rate, steam dairator thermal energy input, and feed water flow rate was estimated as 63^{o}C, 0.56 kg/s, 1550 kW, 8.84 kg/s respectively
- The amount of fuel saving flow rate of 189.49 m^3/h is achieved which corresponding to 6.32 % is achieved.
- The amount of efficiency improvement of 5.1 % is achieved.

2- Effect of using boiler blowdown heat exchanger only

- The feed water outlet temperature, the blowdown flow rate was estimated as 59^{o}C, 0.56 kg/s respectively.
- The percentage of energy saving of 5.52%, is achieved.
  - The amount of fuel saving flow rate of 166 m^3/h is achieved which corresponding to 5.52 % is achieved
  - The amount of efficiency improvement of 5.52 % is achieved

3- Effect of using boiler blowdown heat exchanger and steam dairator

- The feed water outlet temperature from steam dairator estimated as 63 ^{o}C and when it is entered to the heat exchanger, the output value of 99 ^{o}C was achieved.
- The percentage of energy saving of 22.13%, is achieved
- The fuel flow rate is estimated as 664 m^3/h which corresponding to 22.13 % fuel saving.
- Amount of efficiency improvement of 17.86 % is achieved.

From the electric energy saving point of view, some concluded remarks can be listed below

- It is possible to install one MW photovoltaic solar system on the building's roof areas that produce 5 MWh/day electricity to be connected to the national grid

- The total electric power of the industrial plant is estimated as 6.48 MW which is estimated as 155.5 MWh/day
- Based on the plant available sunny areas, the solar system can make electric energy saving by 3.2 % from the total electric energy consumption. This percent can be increased based on available land areas or covering the industrial wastewater treatment plant.

Abbreviations

A_{PV}	Photovoltaic modules Area, m^2
C_{pw}	Specific heat of water, kJ/kg K
EL	Electric Energy Consumed, kWh/day
H	daily global irradiation ($Wh/m^2/d$).
h_g	Latent heat, kJ/kg
H_{sc}	Standard solar irradiation, 1,000 W/m^2.
h_{bdi}	Enthalpy of steam blowdown inlet, kJ/kg
h_{bdo}	Enthalpy of steam blowdown outlet, kJ/kg
m_{bdi}	Mass of steam blowdown inlet, kg
m_{fwi}	Mass of feed water inlet, kg
m_{sd}	Mass of steam dairator, kg
P_{pv}	Photovoltaic modules Power, kW
T_c	temperature correction factor
T_{fwi}	Feed water inlet temperature, °C
T_{fwo}	Feed water outlet temperature, °C
η_{inv}	inverter efficiency
ηPV	photovoltaic efficiency

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Conflict of Interest,

"I hereby confirm that I don't have any conflict of interest related to the manuscript."

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