A comparative study on targeting CO$_2$ emissions reduction from small-scale utility system

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Abstract. This study targets CO$_2$ emission reduction from a particular palm oil refinery scenario presented below where medium-pressure (MP) steam and low-pressure (LP) steam are supplied for process heating. Two different utilities configurations, i.e., steam boiler alone and steam boiler followed by steam turbine are evaluated and compared in terms of their CO$_2$ emission reduction target. Steam boiler alone achieved 20.9% CO$_2$ emission reduction compared to steam boiler followed by steam turbine at the same retrofit design with a minimum temperature driving force, $\Delta T_{\text{min}}$ of 17 °C. Such emission reduction is still considered attractive on global basis if the required electricity comes from the renewable energy resources.

1. Introduction

Emissions of greenhouse gases, such as carbon dioxide (CO$_2$), from the combustion of fossil fuels for process heating and electricity generation is currently the largest contributor to global warming. Improvement in energy system (such as retrofit of heating system), fuel switching to fuel with lower carbon to hydrogen ratio (such as natural gas), CO$_2$ capture and storage, and shift to renewable energy resources (such as solar, wind, and hydroelectric power) can allow significant reduction in global CO$_2$ emissions [1–4]. In this context, some countries like Chile has applied tax on CO$_2$ emissions to encourage the industries to reduce their emissions [5]. European Union, on the other hand, has proposed Emissions Trading System (ETS) to reduce CO$_2$ emissions from the industries through its economic incentives [6, 7]. The ETS provides right to under-emitters who produce carbon emissions less than the allowance allocation (i.e., allowable level of CO$_2$ emissions) to sell their surplus allowances for profit and over-emitters who produce more than their allowance allocation to buy additional allowances [8].

Considerable research attention has been devoted over the past decades to address issues related to CO$_2$ emissions from process industry. For example, Smith and Delaby [9] developed model that relates process minimum energy consumption to flue gas emissions from utilities systems such as furnace, boiler, and turbine. They also define the global counting of CO$_2$ emissions as the sum of emissions from the utilities on a site (i.e., factory) together with those from the outside of the factory fence. Additionally, they proposed a design methodology to minimise the emissions by fuel switching, utilities system design change, process modification, and applying end-of-pipe waste minimisation techniques [10]. Mahmoud et al. [1] developed graphical methodology to reduce CO$_2$ emission from chemical processes by utilising an alternative fuel with lower carbon to hydrogen ratio and reducing the energy requirement by retrofitting the existing heat exchanger network (HEN). In their work, for a given target of CO$_2$ emissions reduction, the fuel switching is initially performed. After the CO$_2$ emissions limit is reached,
Further CO₂ emission reduction is obtained by realising energy saving within the retrofitted HEN at a certain minimum temperature driving force (ΔTₘᵟ). Mahmoud and Sunarso [11] then extended the graphical method by aligning several different factors, i.e., fuel switching, energy saving, investment cost, carbon credit, and payback time to the CO₂ emissions reduction percentage in a single graphical framework that facilitates comprehensive accounting perspective to assist the decision makers in deciding their emissions reduction targets.

Little attention has been given to target CO₂ emissions from small-scale utility system that constitutes single boiler alone or single boiler followed by steam turbine. Majority of works in this topic have so far focus on targeting CO₂ emissions from the stand-alone furnace [1, 11, 12]. Thus, this work aims to investigate and compare CO₂ emissions from small-scale utility system that uses boiler alone or boiler followed by steam turbine.

2. Mathematical model for CO₂ emissions calculation

Carbon dioxide (CO₂) is produced mainly from the combustion of fossil fuels in furnace or boiler to provide heat and steam for process heating and electricity generation. Fossil fuels are combusted by oxygen (O₂) to produce CO₂ according to the following reaction:

\[
C_nH_m + \left( n + \frac{m}{4} \right)O_2 \rightarrow nCO_2 + \frac{m}{2}H_2O \tag{1}
\]

Where \( n \) and \( m \) represent the mole amount of carbon (C) and hydrogen (H) that are present in the fuel, respectively. Air is assumed to be provided in excess amount to ensure complete combustion so that carbon monoxide (CO) is absent.

CO₂ emissions rate (kg s⁻¹) is related to the heat duty of the combusted fuel using the following model [9].

\[
CO_2 \text{ emissions} = \frac{Q_{fuel}}{NHV} \times \frac{C\%}{100} \times \alpha \tag{2}
\]

Where, \( Q_{fuel} \) is the heat duty from fuel (kW), \( NHV \) is the net heating value (kJ kg⁻¹), \( C\% \) is the mass percentage of carbon in the fuel, and \( \alpha \) is the ratio of the molar mass of the oxidised form (CO₂) to the non-oxidised form (C) of the pollutant.

2.1. CO₂ emissions from the steam boilers

Boilers produce steam from the combustion of fuel. A theoretical flame temperature and stack temperature of 1800 °C and 160 °C, respectively, are adopted as typical values. Steam is delivered to the process at the temperature required by the process. Alternatively, the steam can be delivered at a higher temperature and then subjected to the throttling process. In this case, the quality of the steam can be retained by adding boiler water feed following the expansion process; the process of which is defined as desuperheating (Figure 1).
Figure 1. Temperature as a function of enthalpy for the steam generation in the boiler that also illustrates the effect of throttling process [9, 11].

The mass of the boiler feed water needed to desuperheat the steam can be calculated using heat balance by assuming that the boiler feed water is available at 100 °C \( (h = 419 \text{ kJ kg}^{-1}) \) as expressed in Equation (3) [13].

\[
X_{\text{Desup}} = \frac{h_{\text{SUP}} - h_{\text{PROC}}}{h_{\text{SUP}} - 419} \tag{3}
\]

Where \( X_{\text{Desup}} \) is the flow rate of desuperheated boiler feed water per kg of desuperheated steam, \( h_{\text{SUP}} \) is the enthalpy of superheated steam (kJ kg\(^{-1}\)), and \( h_{\text{PROC}} \) is the enthalpy of steam to process (kJ kg\(^{-1}\)).

If an approach temperature, \( T_{\text{app}} \) of 50 °C is assumed in the boiler, the fuel required in the boiler to fulfill the process duty can be calculated using Equation (4).

\[
Q_{\text{fuel}} = \frac{Q_{\text{PROC}}}{L_{\text{Proc}}} (1 - X_{\text{Desup}}) (L_B + h_B) \left[ \frac{T_{\text{TFBT}} - T_0}{T_{\text{TFBT}} - T_B - 50} \right] \tag{4}
\]

Where \( Q_{\text{PROC}} \) is the process heat duty (kW), \( L_{\text{Proc}} \) is the latent heat of steam delivered to the process (kJ kg\(^{-1}\)), \( L_B \) is the latent heat of steam under boiler condition (kJ kg\(^{-1}\)), \( h_B \) is the enthalpy of superheated steam under boiler condition (kJ kg\(^{-1}\)), \( T_{\text{TFBT}} \) is the theoretical flame temperature in the boiler (°C), \( T_0 \) is the ambient temperature (°C), and \( T_B \) is the condensing temperature of steam under boiler condition (°C).

2.2. CO\(_2\) emissions from the steam boilers followed by steam turbine

The combustion takes place in a high pressure boiler fired with any fuel to produce high pressure superheated steam. Then, the steam is passed through a steam turbine to generate lower steam level for process heating (Figure 2).

If an isentropic efficiency of the turbine is specified (e.g., 85%), the power generated and the heat left after the expansion can be calculated using Equations (5) and (6), respectively [9].
\[ W_{ST} = 0.85 \left[ \frac{L_B}{T_B+273} \left( T_B-T_{PROC} \right) + h_{sup,B} \left( \frac{T_{SUP}-T_B}{\ln(T_{SUP}/T_B)} \frac{T_{PROC}}{T_{SUP}-T_B} \right) \right] \]  

(5)

Where \( W_{ST} \) is the actual power generated by the steam turbine (kW kg\(^{-1}\)), \( T_{PROC} \) is the temperature of the saturated process steam (°C), \( h_{sup,B} \) is the enthalpy of superheat under boiler condition (kJ kg\(^{-1}\)), and \( T_{SUP} \) is the temperature of superheated steam from boiler (°C).

\[ h_{out} = h_{sup,B} - \frac{W_{ST}}{0.85} \]  

(6)

Where \( h_{out} \) is the enthalpy of the steam after expansion through a turbine (kJ kg\(^{-1}\)). If \( h_{out} \) is greater than \( h_{PROC} \), it is necessary to desuperheat the steam. On the other hand, if \( h_{out} \) is less than \( h_{PROC} \), then the wet fraction of the steam should be separated (Figure 2).

3. **Case study**

A heat exchanger network of palm oil refinery is considered in this study to demonstrate the calculation of CO\(_2\) emissions from steam boiler alone and steam boiler followed by steam turbine. The work of Haslenda et al. can be consulted for the details of the process flowsheet for oil palm refinery [12]. The grid diagram of the existing HEN of palm oil refinery is shown in Figure 3, where the hot streams (H1 to H4) and the cold streams (C1 to C3) are grouped together in the upper and the lower parts of the grid, respectively. Medium and low pressure steams are used as the utilities to provide process heating.
Figure 3. The grid diagram of the existing heat exchanger network for the palm oil refinery (Q (kW)/A (m²)).

Table 1 lists the utility and cost data for the case study. The total heat capacity (CP) of each stream is calculated by dividing its heat load with the temperature difference of the source and the target (Figure 3). A heat transfer coefficient of 0.2596 W m⁻² K⁻¹ was used for all streams [14]. The existing HEN configuration was designed at \( \Delta T_{\text{min}} \) of 30 °C. This network experienced fouling after three months of operation due to the processing of edible oil. The fouling led to significant increase in the energy consumption. Figure 4 and Figure 5 show the balance grand composite curves of the HEN before and after the fouling, respectively. By comparing Figure 4 to Figure 5, it becomes apparent that the energy consumption after fouling (Figure 5) translates to the requirement for extra utilities as indicated by the dotted upper and lower lines in Figure 5. It is worth noting that fouling phenomenon is generally sensitive to the temperature variation, which in this edible oil processing case takes place significantly above 200 °C [12]. The existing HEN contains two streams that are exposed to temperature higher than 200 °C, i.e., the hot stream H2 and the cold stream C3 (Figure 3). The existing design of HEN at \( \Delta T_{\text{min}} \) of 30 °C can always be retained by washing the fouled heat exchanger [11].

| Type          | \( T_{\text{supply}} \) (°C) | \( T_{\text{target}} \) (°C) | \( H_f \) (kW m⁻² K⁻¹) | \$ kW⁻¹ yr⁻¹ |
|---------------|-------------------------------|-------------------------------|------------------------|-------------|
| Cooling water | 25                            | 30                            | 2.5                    | 18.2       |
| LP Steam      | 143                           | 142                           | 4.5                    | 106.4      |
| MP Steam      | 184                           | 183                           | 4.5                    | 159.6      |

Note: heat exchanger capital cost = 1054 A⁰.⁶⁵ (A = heat exchange area).
Figure 4. Balance grand composite curve at $\Delta T_{\text{min}}$ of 30 °C (before fouling).

Figure 5. Balance grand composite curve at ($\Delta T_{\text{min}}$) of 49.03 °C (after fouling).

Figure 6 displays the energy versus $\Delta T_{\text{min}}$ target curve of the existing HEN of palm oil refinery under study. The change in the energy requirement is quite sensitive to $\Delta T_{\text{min}}$ between 23.5 °C and 49 °C (Figure 6). The energy change with $\Delta T_{\text{min}}$ however becomes minor with an increase in $\Delta T_{\text{min}}$ between 16 °C and 23.5 °C (Figure 6). Thus, to maintain lower energy consumption, we selected $\Delta T_{\text{min}}$ of 17 °C, which is located in the less sensitive range as the target for the retrofit design of HEN. Table 2 presents the calculated CO$_2$ emissions from steam boiler alone and steam boiler followed by steam turbine at $\Delta T_{\text{min}}$ of 30 °C (existing HEN) and $\Delta T_{\text{min}}$ of 17 °C (target retrofit design of HEN). Both utility systems (i.e., steam boiler alone and steam boiler followed by steam turbine) provided emissions reduction of almost 50% from their existing emissions (at $\Delta T_{\text{min}}$ of 30 °C) due to the significant amount of energy saving from the retrofitting of the existing HEN at $\Delta T_{\text{min}}$ of 17 °C. In terms of CO$_2$ emission, Table 2 shows that using steam boiler alone is superior to using steam boiler followed by steam turbine. For
example, steam boiler alone offer 20.9% lower CO₂ emissions compared to the steam boiler followed by steam turbine. However, this reduction in CO₂ emissions may be altered if global CO₂ emission (i.e., total emission from the utilities on the palm oil refinery and from the external source to account for the imported electricity) is considered. In such a case, significant amount of power could be generated by using steam boiler followed by turbine, which may contribute to CO₂ emission reduction in the central power plant. However, using steam boiler alone can still be a competitive option if the imported electricity is generated from the renewable energy resources such as wind, solar, or hydroelectric power.

It is worth noting that for each option of the considered utility systems, further emission reduction beyond 50% can still be achieved if the existing fuel in the combustion devices is modified to fuel with lower carbon to hydrogen ratio and/or end-of-pipe waste minimisation technique such as capture and storage of CO₂ emissions is used.

![Energy versus ΔT_min target curve of the existing HEN of palm oil refinery.](image)

**Figure 6.** Energy versus ΔT_min target curve of the existing HEN of palm oil refinery.

**Table 2.** CO₂ emission from steam boiler alone and steam boiler followed by steam turbine.

| ΔT_min          | CO₂ emission, kg hr⁻¹ (steam boiler) | CO₂ emission, kg hr⁻¹ (steam boiler followed by turbine) |
|-----------------|-------------------------------------|--------------------------------------------------------|
| Existing design (30 ºC) | 84                                  | 103                                                    |
| Retrofit design (17 ºC)   | 40.6                                | 51.3                                                   |

**4. Conclusions**

This work evaluated CO₂ emissions from small-scale utility systems (i.e., steam boiler alone and steam boiler followed by steam turbine) used to supply process heating (MP steam and LP steam) for palm oil refinery. The existing HEN of the palm oil refinery is retrofitted at ΔT_min of 17 ºC, which is located at the less sensitive region on energy versus ΔT_min retrofit curve, to minimise the effect of fouled heat exchanger on the overall performance of palm oil refinery HEN. Such retrofitting of HEN led to almost 50% reduction in CO₂ emissions of both utility systems given the maximised heat recovery within HEN of palm oil refinery. However, the calculated CO₂ emission from steam boiler alone after the retrofit of HEN was lower by 20.9% compared to steam boiler followed by steam turbine on local basis. Steam boiler alone can still be superior to steam boiler followed by steam turbine on global basis if any required electricity by palm oil refinery is generated from the renewable resources. However, if the required electricity is obtained from non-renewable resources, then the trade-off between steam boiler alone case
and steam boiler followed by steam turbine may occur due to the potential of cogeneration offered by the latter case.

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