www.rericjournal.ait.ac.th

Monitoring and Assessment of Energy Efficiency and CO_2 Emissions from Cogeneration Power Plants

Jakrit Upakool[+] and Prapita Thanarak*[,1]

ARTICLE INFO

Article history:
Received 24 September 2020
Received in revised form
03 May 2020
Accepted 19 May 2021

Keywords:
Co-generation power plant
CO_2 emission
Energy efficiency
Parameter to monitor
Power plant monitoring

ABSTRACT

This research study focuses on biomass-based cogeneration power plants. Mechanisms have been adopted to promote and regulate project implementation of cogeneration power plants, improve or increase their energy efficiency, and meet environmental standards, reducing local air pollution and CO_2 emissions. This paper aims to identify the parameters to monitor and assess the improvement in energy efficiency and reduce CO_2 emissions from cogeneration plants. A survey study was first conducted for ten sugarcane processing plants with SPP (10-90 MW) cogeneration plants in the central and northern regions of Thailand. The survey identified parameters used to monitor and control various plant operating conditions such as operating pressures, temperatures, and steam generation flow rates, including preventive maintenance plans to maximize the overall performance of the power plant. A field case study was then conducted for a 25 MW cogeneration power plant in Nakhon Sawan province. The case study involved analyzing the parameters used for monitoring and assessing the best practice operations of a co-generation power plant and evaluating the use of these parameters in analyzing the impacts on the energy efficiency and the CO_2 emissions from the co-generation plant. The case study analysis showed that these parameters used for monitoring and controlling the operation of the co-generation power plants can also be used to monitor and assess the improvement in the energy efficiency of the power plants, and to assess the CO_2 emission reductions achieved by the power plant.

1. INTRODUCTION

Energy is needed to fuel the economy, particularly economic development. Energy supply has primarily been dependent on fossil fuels. However, there is now a need to replace fossil fuel use not just because of the fluctuating and generally rising cost of fossil fuels but also the negative environmental effects of their use, particularly their generation of CO_2 gases that lead to climate change. To promote environmentally friendly national energy strategies that can help mitigate climate change, most countries have been prioritizing renewable energy, especially for electricity generation. Another environmentally friendly strategy that countries are implementing is energy-saving or efficiency programs. Sector-specific energy efficiency strategies are focused on industries, transport, and households. Both renewable energy and energy-saving strategies also reduce dependence on imported energy supply.

[+]Office of the Energy Regulatory Commission, Regional Office (Phitsanulok), Muang, Phitsanulok 65000, Thailand.

*School of Renewable Energy and Smart Grid Technology, Naresuan University, Phitsanulok 65000, Thailand.

[1]Corresponding author:
Tel: + 66 5596 3182, Fax: + 66 5596 3182.
Email: prapitat@nu.ac.th.

Thus today, many countries are increasingly developing and deploying many new energy-efficient and renewable energy technologies. Governments should continue to support these renewable energy and energy-efficient strategies by strengthening policies and regulations and adopting fiscal incentives and appropriate electricity tariffs with these environmental-friendly energy strategies.

Renewable energy-based microgrids can be promoted. A higher percentage share of renewables in the energy supply and higher efficiency in electricity generation, transmission, and distribution can be achieved. All of these can reduce CO_2 emissions from the energy sector and help mitigate climate change.

2. OBJECTIVES OF THE STUDY

One energy-efficient strategy is the use of cogeneration plants in the industry sector. suppose the co-generation power plants are based on biomass fuels. In that case, it is also a renewable energy system, and further reduction of fossil fuel used is achieved, reducing further CO_2 emissions.

This research study focuses on biomass-based cogeneration power plants. Mechanisms have been adopted to promote and regulate project implementation of cogeneration power plants, improve or increase their energy efficiency, and meet environmental standards, reducing local air pollution and CO_2 emissions.

This paper aims to identify the parameters to monitor and assess the improvement in energy efficiency and the reduction of CO_2 emissions from cogeneration plants. Knowing the actual parameter that affects the CO_2 emission will help the regulatory body design the monitoring and assessment scheme.

3. COGENERATION TECHNOLOGY

Cogeneration technology is mostly used in sugarcane, cement, and pulp and paper processing plants. Cogeneration technology optimizes the energy operation in these processing industries.

Cogeneration systems include a back-pressure turbine and an extraction condensing turbine (for the topping cycle) to generate electricity. In sugarcane processing plants, the generated superheated steam goes to the extraction condensing turbine to drive the extraction condensing generator to produce electricity. The steam then exits the generator at a lower pressure and is used for various heating applications in the processing plant. The pressure, steam flow rate, and steam temperature from the extraction condensing turbines can be adjusted. The back-pressure turbine technology is used for generating electricity and steam, at lower pressure and temperature, for use in sugarcane processing. The process diagram for the cogeneration system used in a sugarcane factory, includes a back-pressure turbine, a condensing extraction turbine [1], and other components, is shown in Figures 1 to 2.

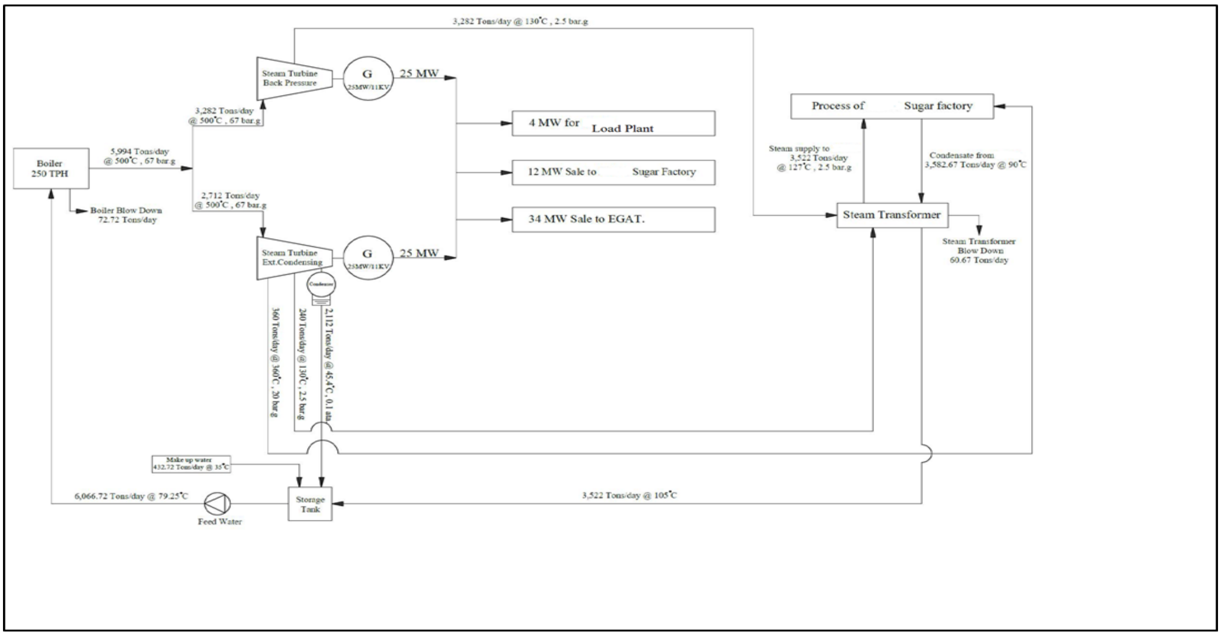

Fig. 1. Combine the technology of back-pressure turbine and condensing extraction turbine.

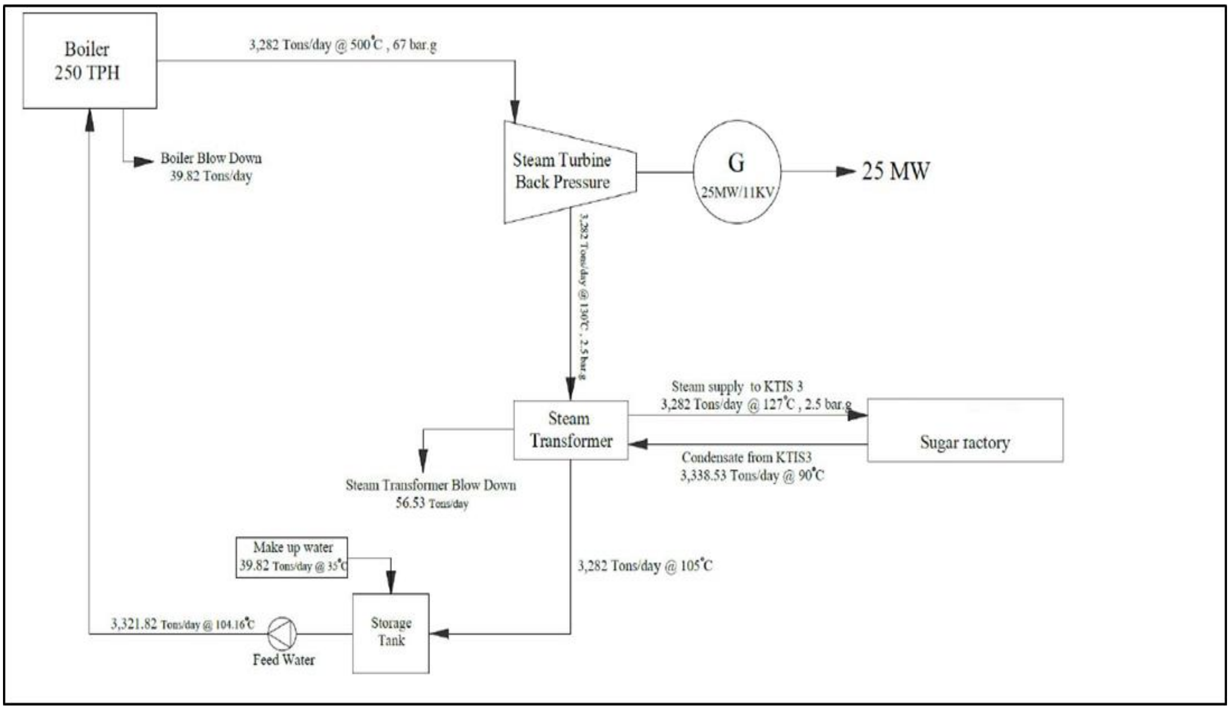

Fig. 2. Backpressure turbine technology.

Performance statistics for various types of cogeneration plants have been published; by types of fuel (see Table 1) from the International Energy Agency (IEA), and by types of fuel and turbine technologies (see Table 2) from the United States Environmental Protection Agency (US EPA).

Table 1. Performance by type of boiler system [2].

Technology of steam generation system	Default Performance
Biomass fired boiler	85%
Natural gas-fired boiler	92%
Coal-fired boiler	80%
Oil fired boiler	85%

Table 2. Type performance of power plants [2].

Technology of electricity generation system	Default performance
Coal	
- Integrated coal gasification combined cycle	50%
- Subcritical	39%
- Supercritical	45%
- Ultra- Supercritical	50%
Natural gas/Oil	
- Steam turbine	44%
- Combine cycle gas turbine	62%
Biomass	
- Integrated biomass Gasification Combined Cycle	40%
- Cogeneration power plant	65%

4. SURVEY STUDY OF COGENERATION PLANTS IN THAILAND

A survey study was first conducted to identify the problems in the operation of cogeneration plants in Thailand. The survey study was conducted for sugarcane processing plants in the central and northern regions of Thailand (covering the provinces of Nakhon Sawan, Petchabun, and Uttaradit). It included ten SPP (Small Power Producers) cogeneration plants. SPPs power capacities range from 10-90 MW. The following are the results of the study:

- Lack of control of the moisture content of the bagasse fuel used in the cogeneration plants. It will be good to control the moisture content, but it is difficult.
- Difficult to control the oxygen-to-fuel ratio. A higher ratio leads to incomplete combustion and lower boiler efficiency, energy stack losses, and overall lower plant efficiency. It is desirable to estimate the amount of oxygen required and the corresponding airflow rate needed.
- Operation supervisors do not have a shift action plan for blowdown and soot blow of the boiler systems. Such an action plan should help control and save water make-up which can reduce wastewater and save fuel.
- Electric companies do not follow preventive maintenance such as wall insulation for boilers and steam piping, prevention of steam leaks, and annual test performance of boilers, turbines, and generators. Preventive maintenance can help improve and increase the performance of the power plants.

The survey also found out that not all parameters to monitor the performance of power plants to help control the operation are collected. The parameters that need to be collected for proper monitoring and assessment of cogeneration plant operation should include the following:

- Pressure and temperature of steam generation in the boiler system. Steam flow rate, temperature, and pressure inlet and outlet turbine and steam quality exhaust turbine.
- Pressure and temperature of the condenser system. Steam flow rate of exhaust turbine.
- Pressure and temperature of cooling tower. Quality of make-up water.
- Blowdown rate of the boiler.
- The moisture of fuel feed in the boiler system, the high heating value of fuel, and the amount of fuel used.

Electric companies need to record operational data on the performance of the different components of the power plants such as the turbines, boiler, condenser, cooling tower, and generator system. These are necessary to improve the performance and efficiency of the power plants and improve the reduction of CO_2 emissions.

5. FIELD CASE STUDY OF A 25 MW COGENERATION PLANT

5.1 Description of the Case Study

A field case study was then conducted after the survey study. The case study involved analyzing the parameters used for monitoring and assessing the best practice operations of a co-generation power plant and evaluating the use of these parameters in analyzing the impacts on the energy efficiency and the CO_2 emissions from the co-generation plant.

The case study was done for a 25 MW cogeneration power plant in Nakhon Sawan province. The plant has an extraction condensing turbine and traveling grate boiler with a capacity to generate steam at 250 tons per hour, as shown in Figures 3. The technical specifications of the main equipment of this co-generation plant are shown in Tables 3 and 4. The proximate and ultimate analyses of the biomass fuel, the sugarcane bagasse, used by the plant are shown in Table 5.

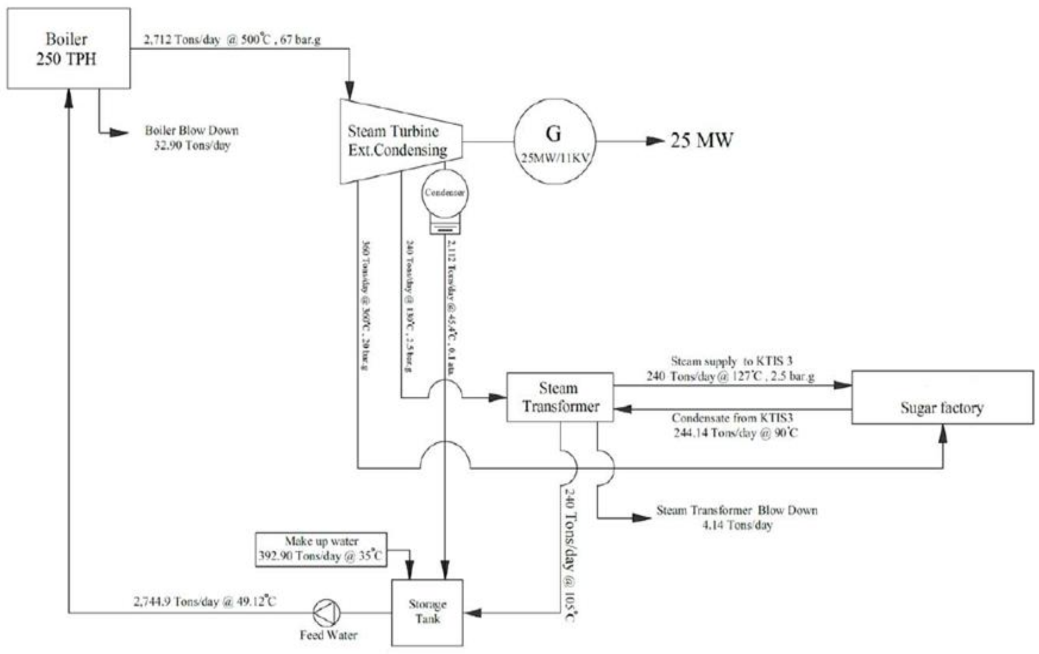

Fig. 3. Extraction condensing turbine technology [1].

Table 3. Details of boiler operation.

Ambient Temperature and % RH	34 °C, 70 %RH
Boiler capacity	• Steam generation 250 ton/hour • Pressure 68 bar, 500 °C • FW 105 °C
Load factor	• 90 % at average • Steam flow rate 218 ton/hour • Pressure 65 bar, 485 °C
Fuel	• Bagasse at 56 % moisture • HHV 6,447.67 kJ/kg
Excess air ration	• 2.55 at exhaust gas (O2 11.85%)

Table 4. Details of extraction condensing steam turbine.

Turbine type	Extraction condensing
Turbine capacity	• Steam flow rate 150 ton/hour • Pressure 65 bar, 480 °C
Extraction 1	• Steam flow rate 55 ton/hour • Pressure 2.5 bar, 130°C
Extraction 2	• Steam flow rate 45 ton/hour • Pressure 0.10 bar, 32°C
Condensing	• Steam flow rate 45 ton/hour • Vacuum pressure -0.90, 48.5°C
Load factor	• Normal load • Steam flow rate, 113 ton/hour • Pressure 65 bar, 480°C, 5 MW
Steam turbine generator	25 MW
The efficiency of turbine generator	95 %

Table 5. Lab test: Proximate and ultimate analysis of sugarcane bagasse.

Parameter	Bagasse 100 %	Ash
Proximate Analysis		
Moisture	56	-
Ash	4.54	-
Carbon	45.03	6.887
Ultimate Analysis		
Hydrogen	0.82	-
Nitrogen	0.142	-
Oxygen	44.31	-
Sulfur	0.12	
Chlorine	4.00	
HHV: High Heating Value = 6447.67 kJ/kg		

5.2 Methodology for Case Study

The parameters and equations used for monitoring the performance of the cogeneration power plants, based on the plant components, their operating conditions, and the plant biomass fuel consumption, are in Table 7 (shown at the end of this paper). These parameters and equations determine the overall performance of the power plant and its components; the boiler, steam turbines, and the generator system, including the heat losses of the piping system and the boiler walls.

The monitoring and assessment of the energy efficiency of and the CO_2 emission from the power plants include:

- The assessment of the boiler efficiency using the direct method and the heat-loss method (indirect method), was based on equations 2 to 14 (refer to Table 7) for an over two-hour duration test at steady-state (JIS B8222:1993; land boiler including hot water boiler method) [3]. The operational data collected using SCADA monitor and fuel gas analysis included the high heating value of fuel, steam mass flow rate, the steam temperature, steam, stack emissions (*i.e.*, CO, CO_2, O_2, NOx, and SO_2), the boiler blowdown rate, steam used for blowing soot and clearing pipe surface scales, and temperature of surface boiler and main steam piping.
- The assessment of turbine efficiency applied the ASME PTC-2004 Steam Turbine method based on Equations 18 and 19 (refer to Table 7) [4]. The acceptance test was scheduled as soon as the first turbine was loaded. At steady-state operation or regular load operation, the operational data collected using the SCADA monitor and the SSTM (Steam System Modeler Tool) software, included steam flow rate, pressure, temperature of inlet, outlet turbine system, and steam quality at the exhaust turbine and its effect on the entropy of the system and lowering of turbine performance [29].
- The assessment of the generator efficiency was based on design values of about 95-98% of electricity generation. The annual performance test reported on the ratio between the generator output and the generator output plus generator loss as given by Equation 1[22].
- The assessment of heat loss of the main steam pipe and the surface temperatures of insulated pipe and equipment system applied the standard practices for determining the heat gain or loss using a computer program. The U.S. occupational safety and health administration (OSHA) sets a limit of maximum skin temperature of 140°F (60°C) after five seconds of exposure) [8]. The data collected for the assessment of the operation include the heat loss of the main steam pipe recorded on the worksheet, thermal camera scan of the temperature of more than 60°C, the surface temperature of the pipe, the diameter of the pipe (using 3E Plus software [28]), ambient temperature, wind speed, the temperature of steam, type of pipe, and type of insulation. Based on Equations 19 to 21 (refer to Table 7), the following data were collected to determine heat gain or loss and the surface temperature of insulated pipes, to record the operation parameters of the power plant; air temperature, average surface temperature, diameter for cylinder, average wind speed [6].
- The assessment of the performance of the power plants was based on the first law of thermodynamics. The assessment of the heat processes (internal energy and work system) was determined following Equation 1 (refer to Table 7); included the results of the efficiency tests of the boiler, turbine, and generator set.
- The monitoring and assessment of the energy-efficiency of the power plants by comparing annual energy efficiency tests with the design values of the power plants, including the boilers, turbines, and generators, was done to determine the lower efficiency of the equipment and to help improve the efficiency of the power plants.
- The methodological tool: "Determination of The Baseline Efficiency of Thermal or Electric Energy Generation Systems - Version 02.0" [2] was used for the boiler travel gate, generator system,

backpressure turbine, and extraction is condensing turbine. Please see Table 8.

- The assessment of CO_2 emissions from power plants used either equation 23-28 or 17 (see Table 7), which are based on the "Guidelines for Methodological Tool for Baseline Assessment: Project and Leakage Emissions from Electricity Consumption and Monitoring of Electricity Generation - Version 03.0" of the UNFCCC (United Nations Framework Convention on Climate Change) [7].
- The tools used to record the parameters to assess CO_2 emission include SCADA, datasheet records (such as electricity generation, fuel consumption, and fuel travel distance). The data also included the fuel high heating value, amount of fuel for boiler start-up, amount of fuel used for fuel transport, and amount of electricity sold to the grid (*i.e.*, Provincial Electricity Authority, PEA).
- The baseline CO_2 emission of a project can be applied as a performance indicator of the operation of a power plant. Electric companies need to monitor the other parameters that impact the CO_2 emissions and the efficiency of the power plants, such as fuel use for fuel transport and boiler start-up, source of fuel, and the combustion quality of fuel.

5.3 Monitoring and Assessment of Best Practice Operations

This study focused on an analysis of how to improve the efficiency of power plants power plants' efficiency in power plants, and how to improve power plants' efficiency on improving power plants' efficiency by improving power plants' efficiency based on the experiences and best practices operations.

a) Improvement Operation Boiler System

- Control moisture content at 50 %
- Control O_2 of exhaust gas at 5.85 %
- Control blow down at 610.87 kg/hour

The operation data to improve the operation of the boiler system and from the controlling plant, the operation is shown in Tables 6, 9 to 13 below.

b) Improve the Insulation of Main Steam Pipe

The insulation material had the following specifications: mineral fiber pipe, type I, C547-15, with an insulation thickness of 15 mm. The parameters to calculate the heat loss of the main steam pipe are shown in Tables 10 to 11.

Table 6. Parameters for calculation of stack gas loss (L_1).

Description	Parameter	Unit	Data
$L_1 = G \times C_g x(t_g - t_o)$, $L_{1h} = L_1 + 25(9h + \omega)$			
The temperature of flue gas	t_g	°C	130.2
Temperature of surrounding	t_o	°C	43.95
Specific heat capacity in flue gas	C_g	kJ/kg °C	1.38
Flue gas of mass flow rate	G	m^3/kg	2.10
Hydrogen	h	%	0.82
Moisture in fuel	ω	%	50
Stack gas loss	L_1	kJ/kg	1,834.74

Table 7. Efficiency assessment of power plant and its components.

Power plant system and components	Method	Technology	Tool	Measure	Equation
Performance of power plant	The first law of thermodynamics theory, such mass balance and conservation of energy principle to heat and thermodynamic processes (internal energy, heat, and system work) [1], [3] ,[4], [6] ,[22], [28], [29]	- Boiler travel gate - Extraction condensing turbine - Backpressure turbine - Generator system	-Supervisory Control and Data Acquisition: SCADA - 3E Plus Soft ware - SSTM software	Overall performance power plant.	Performance of power plant $\eta_{overall} = \eta_{boiler} * \eta_T * \eta_G$ Equation 1 when ; $\eta_{overall}$ = Overall energy efficiency of power plant ; % η_{boiler} = Efficiency of boiler system; % $\eta_{Turbine}$= Efficiency of turbine; % $\eta_{Gernerator}$ = Efficiency of generator; % (the ratio generator output and generator output plus generator loss.)
Boiler system and Steam turbine	JIS B8222:1993; Land Boiler including hot water boiler method. [1], [3], [5], [6], [8]	-Boiler travel gate	- Flue gas analysis -Flow meter -Thermocouple -Pressure gauge -Belt load cell -Moisture analysis - Infrared camera -Supervisory Control and Data Acquisition: SCADA -Test report fuel composition.	CO_2, CO, SO_2, NO_x, and O_2 exhaust gas -Steam flow rate -Feed water -Blow down rate -Temperature of steam -Temperature of feed water -Temperature of blow down rate -Pressure of steam -Pressure of feed water -Pressure of blowdown rate - Weight of fuel feed - Moisture of fuel -Heat loss of wall -Monitor parameter of operation power plant - C %, S%, W%, Ash, O%, N%, and HHV	Indirect method $\text{Heat loss} = L_h = L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_{pipe}$ Equation 2 when; L_1 = Fuel gas loss of boiler system; kJ/kg L_2= Soot blow loss of boiler system; kJ/kg L_3= Incomplete combustion loss of boiler system; kJ/kg L_4= Unburned loss of boiler system; kJ/kg L_5= Radiation loss boiler system; kJ/kg L_6= Blowdown loss boiler system; kJ/kg L_{pipe} = Pipe loss; kJ/kg Flue gas loss, $L_1 = G x C_p x (T_g - T_a)$ Equation 3 when; G = Flue gas of mass flow rate ; m^3/kg C_p = Specific heat of flue gas exhaust ; kJ/m^3 °K T_g = Temperature of flue gas exhaust ; °K T_a = Temperature of environment ; °K $G = G_o + G_w + [A_o x (m - 1)] + G_{w1}$ Equation 4 when; G_o= Amount of theoretical flue gas; m^3/kg G_w = Amount of steam generation by burn and heat derived from moisture in fuel; m^3/kg A_o = Amount of theoretical of air ; m^3/kg m = Ration of excess air; % G_{w1} = Amount of steam due to hygroscopic moisture in combustion air; m^3/kg $G_o = \frac{1}{100}\left[8.89 \text{ x } C_1 + 21.1\left(h - \frac{O}{8}\right) + 3.3 \text{ x } S + 0.8 \text{ x } N\right]$ Equation 5

Power plant system and components	Method	Technology	Tool	Measure	Equation
					when; C_1 = Carbon in combustion ; % h = hydrogen in fuel ; % O = oxygen in fuel ; % S = Sulfur in fuel ; % N = Nitrogen in fuel ; % $A_O = \frac{1}{100}\left[8.89 \times C_1\ 26.7\left(h - \frac{O}{8}\right) + 3.3 \times S\right]$ Equation 6 when; C_1 = Carbon in combustion ; % h = Hydrogen in fuel ; % O = Oxygen in fuel ; % S = Sulfur in fuel ; % $m = \frac{21}{21-79\left[\frac{(O_2)-0.5(CO)}{(N_2)}\right]}$ Equation 7 when; O_2 = Oxygen in flue gas; % CO = Carbon in flue gas; % N_2 = Nitrogen in flue gas; % $G_w = \frac{1}{100}[1.24(9h + \omega)]$ Equation 8 when; h = Hydrogen in fuel ; % ω = Moisture in fuel % $G_{w1} = 1.61zmA_o$ Equation 9 when; A_o = Amount of theoretical of air; m^3/kg m = Ration of excess air; % z = Absolute humidity of air to combustion; % $L_2 = W_b(h_g - h_{fw})$ Equation 10 when; W_b = Amount of steam using to soot blow; kg/hr h_g = Enthalpy of steam using to soot blow; kJ/kg h_{fw} = Enthalpy of feed water ; kJ/kg $L_3 = 26.1[G_o + (m-1)A_O] \times CO$ Equation 11 when; CO = Carbon in flue gas ; % G_o = Amount of theoretical flue gas; m^3/kg m = Ration of excess air; %

Power plant system and components	Method	Technology	Tool	Measure	Equation
					$L_4 = 339 x C_2$ Equation 12 when; C_2 = Compare carbon surplus and carbon in fuel $L_5 = \frac{3{,}600 \times Q_w}{\dot{m}_f}$ Equation 13 when; Q_w = Amount of heat loss at wall boiler or surface pipe ; kW $\dot{m}_f$ = Amount of fuel using; kg/hr $L_6 = \dot{m}_{bd} \frac{(h_{bd} - h_{FW})}{\dot{m}_f}$ Equation 14 when; $\dot{m}_{bd}$ = flow rate of blowdown; kg/hr h_{bd} = Enthalpy of blowdown rate; kJ/kg h_{FW} = Enthalpy of feed water; kJ/kg Efficiency of boiler system $\eta = \left(1 - \frac{L_h}{H_h + Q}\right) x\ 100\%$ Equation 15 when; η = Efficiency of boiler system; % L_h = Total heat loss of boiler system; kJ/kg H_h = Heat loss of flue gas reference high heating value per kg; kJ/kg Q = Heat supplement in boiler system; kJ/kg Flue saving $FS = \frac{\eta_{new} - \eta_{old}}{\eta_{new}} x\ \dot{m}_f$ Equation 16 when; FS = Fuel saving; ton/hr $\dot{m}_f$ = Fuel using; ton/hr η_{new} = Efficiency of after improvement; % η_{old} = Efficiency of before improvement; % CO_2 reduction emissions CO_2 Emission $= EF \times FS$ Equation 17 when; EF = Emission factor; $kgCO_2$/ton (*ref ; CO_2 emission EPA for wood and wood residuals = 1,640 $kgCO_2$/ton*) FS = Fuel saving; kg/hr

Power plant system and components	Method	Technology	Tool	Measure	Equation
Boiler system and steam turbine	ASME PTC-2004; Steam turbine [4], [22], [29]	-Extraction condensing turbine -Backpressure turbine	-Flowmeter -Thermocouple -Pressure gauge SSTM software	-Steam inlet turbine -Steam outlet turbine -Temperature of steam inlet - Temperature of the steam outlet -Pressure of steam inlet turbine -Pressure of steam outlet turbine -Pressure of vacuum condensing -Assessment performance of a turbine	Performance of steam turbine. $\eta_{isentropic} = \frac{\text{Energy out}_{1-2} + \text{Energy out}_{1-3}}{\text{Energy out}_{1-2'} + \text{Energy out}_{1-3'}}$ Equation 18 when; Energy out 1-2 = Energy output of high pressure and lower pressure isentropic process; kW Energy out 1-3 = Energy output of high pressure and condensing isentropic process; kW Energy out 1-2' = Energy output of high pressure and lower pressure ideal process; kW Energy out 1-3' = Energy output of high pressure and condensing ideal process; kW $\text{Energy Out} = \dot{m}_s(h_{inlet} - h_{out})$ Equation 19 when; $\dot{m}_s$ = mass flow rate ; ton/hr h_{inlet} = inlet specific enthalpy ; kJ/kg h_{out} = outlet specific enthalpy ; kJ/kg
heat loss of steam pipe and wall of the boiler	Standard Practice for Determination of Heat Gain or Loss and the Surface Temperatures of Insulated Pipe and Equipment System using a Computer Program. (Designation: C680 -89 Reapproved 1995); Case 2 Cylindrical Section, ASTM C 585 rigid and Flexible [5], [6] The U.S. Occupational Safety and Health Administration (OSHA) sets a limit of a maximum skin temperature of 140°F (60°C) after five seconds of exposure).[8] -	- Steam Pipe - Wall - Insulation of using	-3E Plus Soft ware - Infrared camera -Data wind speed in location power plant	-Heat loss of steam pipe includes convection and radiation. - Heat loss walls of the boiler include convection and radiation.	Heat gain of loss and the surface temperatures of insulated pipe and equipment system. $h = h_{cv} + h_{rad}$; kW Equation 20 when; h_{cv} = Convective surface coefficient , W/m^2.K^4. h_{rad} = Radiative heat transfer rate, W/m^2.K. $h_{red} = \frac{E_{miss} \times 5.67 \times 10^{-8} (t_a+459.6)^4 - (t_s+459.6)^4}{(t_a - t_s)}$ Equation 21 when; h_{rad} = Radiative heat transfer rate, W/m^2.K. E_{miss} = Effective surface emittance 5.67 x 10^{-8} = Stefan – Boltzman constant, W/m^2.K^4. t_a = Air temperature, K . t_s = Average surface temperature, K . $h_{cv} = C \times (\frac{1}{d})^{0.2} \times (\frac{1}{t_{avg}})^{0.181} \times \Delta t^{0.266} \times \sqrt{1 + 1.277 \times wind}$ Equation 22 when; h_{cv} = Convective surface coefficient, W/m^2.K^4. d = Diameter for cylinder in , m . For flat surface and large cylinders d > 24, use d =24. t_{avg} = Average temperature of air film K = $(t_s + t_a)$/2. Δt = Surface to air temperature difference K = $(t_s - t_a)$. C = The values of constant of shape and heat flow condition

Table 8. Method for Assessment of CO_2 Emission from the Power Plant.

Method	Technology	Tool	Measure	Equation
Methodological tool baseline; project and/or leakage emissions from electricity consumption and monitoring of electricity generation version 03.0.[7]	- Boiler travel gate - Truck of fuel - Generator system	- Supervisory Control and Data Acquisition: SCADA - Data sheet record - electricity generation - fuel consumption - distance truck	- CO_2 emission of project	**Determine electricity generation.** Equation 23 Annual CH_4 released = HHVof bagasse used by project x CH_4 emission factor for bagasse x GWP of CH_4 when; Annual CH_4 released = emission CH_4 from combustion of fuel; tCO_{2e}/yr HHV= High heating value of bagasse; kJ/kg CH_4= emission factor fuel; tCH_4/kJ GWP of CH_4 = Global warming potential of CH_4; tCO_{2e}/tCH_4 **Determine distance transport of fuel.** Equation 24 Distance traveled = Total bagasse consumed by project x Truck capacity x Return trip distance to supply-side when; Total fuel consumed by the project; ton/yr Truck capacity; ton Return trip distance to supply site; km **Determine Emissions from the transport of fuel.** Equation 25 Annual emission = Emission factor x Distance travelled when; Emission factor = from fuel consumption in transport of fuel; $tCO_{/2e}$/km Distance travelled; km/yr **Determine emission of a start-up.** Equation 26 Annual CH_4 released = HHV of fuel using to start-up x emission factor fuel x GWP of CH_4 when; Annual CH_4 released = emission CH_4 from combustion of fuel; tCO_{2e}/yr HHV = high heating value of fuel using to startup; kJ/kg GWP of CH_4 = Global warming potential of CH4; tCO_2/tCH_4 Emission factor fuel = emission of fuel using to start up; tCH_4/kJ **Determine amount CO_2 emission of electricity exported by project.** Equation 27 CO_2emission = Amount electricity exported x CO_2 emission factor when; CO_2 emission = amount CO_2 emission of electricity exported; tCO_2/yr Amount electricity exported, MWh CO_2 emission factor; tCO_2/MWh **Determine baseline CO_2 emission of project** Equation 28 Baseline CO_2 Emission = Emission from grid electricity + Emission from fueled electricity generation - Emission from transportation of fuel - Emission from start-up; tCO_2/yr
Methodological tool; Determining the baseline efficiency of thermal or electric energy generation systems version 02.0 [2].	-Boiler travel gate - Generator system -Backpressure turbine -Extraction condensing turbine	- Supervisory Control and Data Acquisition: SCADA -3E Plus Soft ware - SSTM software Datasheet record - electricity generation - fuel consumption	- Compare the Design value of equipment such as - Boiler system - Generator system - Steam turbine	**Design Value of main equipment** - Boiler system - Generator system - Backpressure turbine - Extraction condensing turbine

Table 9. Parameters for calculating carbon loss (L_2).

Description	Parameter	Unit	Data
$L_2 = 126.1(G_o + (m-1)A_o)CO$			
Amount of theoretical flue gas	G_o	m^3/kg	0.77
Amount of theoretical air	A_o	m^3/kg	0.85
A ration of excess air	m	%	1.426
Carbon in flue gas	CO	%	0.1063
Carbon loss	L_2	kJ/kg	15.15

Table 10. Data to assess heat loss of main steam pipe.

Location	Type of Pipe	Temperature of Surface of Pipe (°C)	NPS Pipe Size (mm)	Wind Speed (m/s)	Length(m)
Main steam Pipeline	Stainless Steel	417	150	3.6	1

Table 11. Parameters for calculating heat radiation loss from Pipe (L_{pipe}). (Determine heat loss by 3E Plus Program).

Description	Parameter	Unit	Data
$L_5 = \frac{3,600 \text{ x } Q_w}{\dot{m}_f}$			
Heat loss of main steam pipe	$Q_{main\ steam}$	kW	8.499
Heat loss of main steam pipe (improve)	$Q_{main\ steam}$	kW	0.1793
Amount of heat loss steam pipe (improve)	Q_{pipe}	kW	18.30
Amount of fuel using	m_f	ton/hour	121
Radiation loss wall of steam pipe	L_5	kJ/kg	0.544

Table 12. Parameters for calculating blow down loss (L_6).

Description	Parameter	Unit	Data
$L_6 = \dot{m}_{bd}\frac{(h_{bd} - h_{FW})}{\dot{m}_f}$			
A flow rate of blowdown	$\dot{m}_{bd}$	kg/hour	610.87
Enthalpy of blowdown rate	h_{bd}	kJ/kg	1,485.10
Enthalpy of feed water	h_{FW}	kJ/kg	482.6
Amount fuel using	$\dot{m}_f$	kg/hour	121,000
Blowdown loss	L_6	kJ/kg	5.06113

Table 13. Parameters for calculating improvement of performance of the boiler system.

Description	Parameter	Unit	Normal Operation	Improve Operation
$\eta_{indirect} = (1 - \frac{L_{stack} + L_{soot\ blow} + L_{CO\ loss} + L_{radiation\ loss} + L_{blow\ down\ loss} + L_{unburned\ loss} + L_{Steam\ pipe\ loss}}{HHV + HG})$				
High Heating Value	HHV	kJ/kg	6,447.67	6,447.67
Stack Gas Loss	L_1	kJ/kg	2,262.06	1,834.74
Carbon Loss	L_2	kJ/kg	37.68	15.15
Soot Blown Loss	L_3	kJ/kg	-	-
Unburned Loss	L_4	kJ/kg	113.83	113.83
Radiation Loss	L_5	kJ/kg	32.38	32.38
Blow Down Loss	L_6	kJ/kg	28.24	5.06
Main Steam Pipe Loss	L_7	kJ/kg	0.83	0.544
Another Heat Input	HG	kJ/kg	-	-
Performance of Boiler	$\eta_{indirect}$	%	61.61	65.98

c) Improve Operation of Extraction Turbine

This experiment used steam recovery to preheat the deaerator system and save fuel consumption by increasing the performance of the condensing extraction turbine. The parameters to control operation and the method for assessing the turbine performance are shown in Tables 14 and 15 and Figure 4.

Table 14. Operation data of extraction condensing turbine.

Parameter	Data Operation
Not using steam exhaust preheat temperature lower deaerator system	
Mass flow rate inlet turbine	110.23 ton/hour
Amount steam drum upper for increase heat in the deaerator system.	2.8 ton/hour
Using steam exhaust preheat temperature deaerator system	
Mass flow rate inlet turbine	106.8 ton/hour
Amount steam lower pressure for increase heat in deaerator system	3.02 ton/hour

Table 15. Operation data of deaerator system and feed water system.

Parameter	Data Operation
Deaerator System	
Steam Inlet	3.02 ton/ hour
Pressure	2.5 bar
Temperature	139°C
Vented Steam	
Pressure	1.12 bar
Temperature	122.3 °C
Mass flow rate	0.39 ton/ hour
Feed Water System	
Pressure	3 bar
Temperature	115.2°C
Mass flow rate	194.37 ton/ hour

Table 16. Parameters for calculation of performance of extraction condensing turbine.

Description	Parameter	Unit	Normal Operation	Improve Operation
Isentropic Process of HP to LP				
Mass flow rate inlet	$\dot{m}_s$	ton/hour	-	3.02
Enthalpy inlet	h_{inlet}	kJ/kg	-	3,355.4
Enthalpy out	h_{outlet}	kJ/kg	-	2,732.2
Energy out	Energy out_{1-2}	kW	-	552.9
Ideal Process of HP to LP				
Mass flow rate inlet	$\dot{m}_s$	ton/hour-		3.02
Enthalpy inlet	h_{inlet}	kJ/kg	-	3,355.4
Enthalpy out	h_{outlet}	kJ/kg	-	2,655.1
Energy out	$\text{Energy out}_{1-2'}$	kW	-	587.5
Isentropic Process of HP to Cond				
Mass flow rate inlet	$\dot{m}_s$	ton/hour	110.23	106.8
Enthalpy inlet	h_{inlet}	kJ/kg	3,355.4	3,355.4
Enthalpy out	h_{outlet}	kJ/kg	2,428.4	2,428.4
Energy out	Energy out_{1-3}	kW	28,384	27,502.6
Ideal Process of HP to Cond.				
Mass flow rate inlet	$\dot{m}_s$	ton/hour	110.23	106.8
Enthalpy inlet	h_{inlet}	kJ/kg	3,355.4	3,355.4
Enthalpy out	h_{outlet}	kJ/kg	2,153.2	2,153.2
Energy out	$\text{Energy out}_{1-3'}$	kW	36,810.5	35,665.1
Isentropic Efficiency = $\frac{\text{Energy out}_{1-2} + \text{Energy out}_{1-3}}{\text{Energy out}_{1-2'} + \text{Energy out}_{1-3'}}$			77.1 %	77.38%

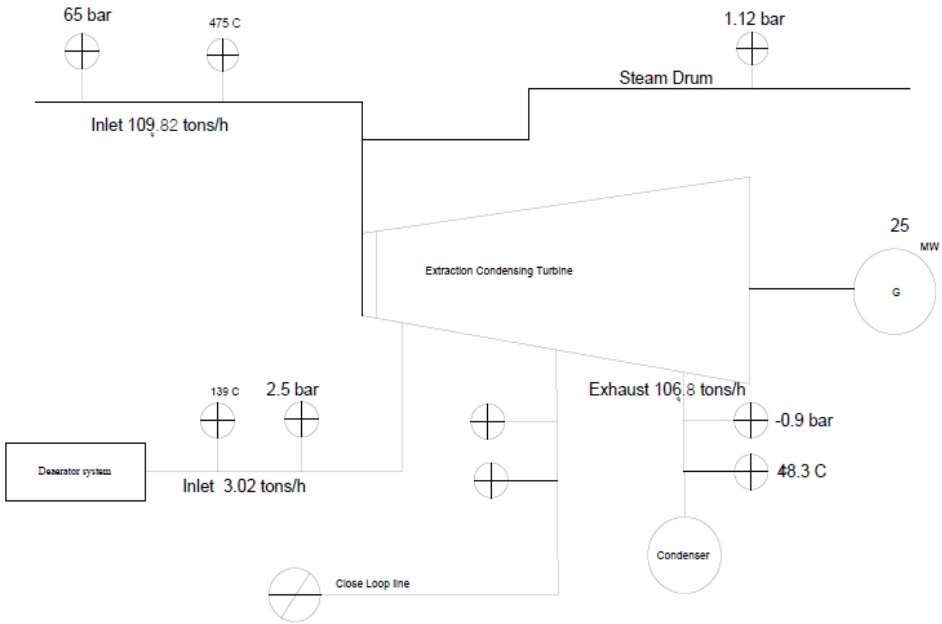

Fig. 4. Diagram using steam recovery to preheat at the deaerator system.

6. DISCUSSION OF RESULTS

The field study the identifying parameters to monitor and assess the improvement in energy efficiency and reducing CO_2 emissions from cogeneration plants was based on a case study on monitoring the best practice operations of a 25 MW cogeneration power plant in Nakhon Sawan province.

The results of applying best-practice operations of the co-generation plant led to controlling the moisture content at 50%, controlling O_2 concentration of exhaust gas at 5.85%, blowdown rate at 610.8kg/hour, improvement of the fiber insulation of the main steam pipe (type I, C547-15 at thickness 15 mm), and steam recovery of 3.2 ton/hour at the deaerator for preheating. Improvement in energy efficiency and reductions of CO_2 emissions.

The study, which used the parameters for monitoring and controlling the best practice operations, showed that these parameters (and the accompanying equations) can also determine improvement in energy efficiency and reduction of CO_2 emissions.

The analysis done using the parameters (and accompanying equations) yielded values for the efficiencies power plant and its components. The results showed that the efficiencies of the boiler system, the extraction condensing turbine, and the overall power plant efficiency increased by 4.37%, 0.28%, and 2.79%, respectively (see Table 17). Similarly to Mohd Parvez,'s assumptions and studies of biomass gasification, Gas Turbine Inlet Temperature (GTIT) is 1150 – 1250 K, approach temperature 288 K and turbine inlet pressure during 30 – 70 bar and efficiency was about 35.49 – 39.99% [17]-[18]. These led to a fuel saving of 6,494.25 ton/year and reduced CO_2 emissions by 10,650.57 tCO_2/year.

7. CONCLUSION

This study identified the standard parameters to monitor and control the operation of cogeneration plants, especially biomass cogeneration plants, through a survey in the sugar processing industry. The survey identified parameters that are used to monitor and control various plant operating conditions such as operating pressures, temperatures, and steam generation flow rates, including preventive maintenance plans to maximize the overall performance of the power plant.

Through a case study of a 25 MW cogeneration plant, the study analyzed how these parameters and methodologies (*i.e.*, accompanying equations) were used to determine the impacts of best practice operations of power plants.

The case study analysis showed that these parameters and used for monitoring and controlling the operation of the co-generation power plants can also be used to monitor and assess the improvement in the energy efficiency of the power plants, and to assess the CO_2 emission reductions achieved by the power plant.

Table 17. Parameters for calculation of the improvement in the overall performance of operation the power plant.

Description	Parameter	Unit	Data
Efficiency of Boiler	η_{old}	%	61.61
	η_{new}	%	65.98
	$\dot{m}_f$	ton/hour	121
Improvement Efficiency		%	4.37
$FS = \frac{\eta_{new} - \eta_{old}}{\eta_{new}} \times \dot{m}_f$		ton/hour	8.01
Efficiency of Extraction Condensing Turbine	η_{old}	%	77.1
	η_{new}	%	77.38
	$\dot{m}_f$	ton/hour	121
Improvement Efficiency		%	0.28
$FS = \frac{\eta_{new} - \eta_{old}}{\eta_{new}} \times \dot{m}_f$		ton/hour	0.437
Power Plant Efficiency	η_{boiler}	%	65.98
	$\eta_{Extraction\ Turbine}$	%	77.38
	$\eta_{generator}$	%	95
	$\eta_{oveall_{new}}$	%	48.50
$\eta_{overall\ old} = \eta_{boiler} \times \eta_{turbine} \times \eta_{generator}$		%	48.50
$\eta_{overall\ old} = \eta_{boiler} \times \eta_{turbine} \times \eta_{generator}$		%	45.71
Improvement Efficiency		%	2.79
Total Fuel Saving Note: Operation power plant 933 hour/year		ton/year	6,494
CO_2 Reduction (ref ; CO_2 emission EPA for wood and wood residuals = 1,640 $kgCO_2$/ton)		tCO_2/ year	10,650

REFERENCES

[1] Ruamphol Biopower Company Limited. 2019. Cogeneration Power Plant Install Capacity 50 MW. Bagasse Fuel, Nakon Sawan, Thailand.

[2] The United Nations Framework Convention on Climate Change (UNFCCC). 2015. Methodological tool determining the baseline efficiency of thermal or electric energy generation systems, Version 02.0. UNFCCC, Bonn, Germany.

[3] Japanese Industry Standard (JIS), 1993. TJIS B 8222:1993. Land boilers-Heat balancing: Method Assessment Energy Efficiency of Boiler Systems. Japanese Standards Association, Japan.

[4] The American Society of Mechanical Engineers (ASME), 2013. ASME PTC 4-2013. Fired Steam Generators Performance Test Code. ASME, New York.

[5] The American Society for Testing and Materials (ASTM), 2010. Designation: C585-10. Standard Practice for inner and Outer Diameters of Thermal Insulation for Nominal Sizes of Pipe and Tubing. ASTM, West Conshohocken, USA.

[6] The American Society for Testing and Materials (ASTM), 1995. Standard Practice for Determination of Heat Gain of Loss and the Surface Temperatures of Insulated Pipe and Equipment System by the Use of a Computer Program. (Designation: C680-89 Reapproved 1995); Case 2 Cylindrical Section, ASTM C 585 rigid and Flexible. ASTM, West Conshohocken, USA.

[7] The United Nations Framework Convention on Climate Change (UNFCCC), 2015. Method Baseline CO_2 Emission Such as Project Design Document from CDM –SSC-PDD – Version 03 With Method to Make of Clean Development Mechanism Project Design Document With Application of a Baseline and Monitoring Methodology.UNFCCC, Bonn, Germany.

[8] The U.S. Occupational Safety and Health Administration (OSHA)., 2017. Regulation of Personal Protective Equipment. Sets A Limit of A Maximum Skin Temperature of 140°F (60°C) After Five Seconds of Exposure. [On-line serial], Retrieved May 5, 2019 from the World Wide Web: https://www.osha.gov/personal-protective-equipment/standards.

[9] Niraj K. and P. Kruten. 2017. Exergy analysis of thermal power plant for full load and part load condition. *International Journal of Advance Engineering and Research Development* 4(6).

[10] Yung C., 2015. Energy and exergy analyses of biomass cogeneration system. *The Faculty of Engineering and Applied Science*. University of Ontario Institute of Technology.

[11] Mahlia T.M.I., Lim J.Y., Aditya L., Riayatsyah T.M.I., and Abas Nasruddin A.E.Pg, 2018. Methodology for implementing power plant efficiency standards for power generation:

Potential emission reduction. *Clean Technologies and Environmental Policy*: 309–327.

[12] Feng T.T., Gong X.L., Guo Y.H., Yang Y.S, and Dong J, 2019. Regulatory mechanism design of GHG emissions in the electric power industry in China. *Energy Policy* 131: 187-201.

[13] Office of The Energy Regulatory Commission (ERC). 2019. Database License of Electricity Generation., Licensing Process., and Regulation Operation of Power Plants Since 2019 . [On-line serial], Retrieved May 20, 2019 from the World Wide Web: http://app04.erc.or.th/ELicense/Licenser/05_Reporting/504_ListLicensing_Columns_New.aspx?LicenseType=1

[14] Energy Policy and Planning Office (EPPO). 2019. Statistics CO_2 Emission of Power Plants Sector Since 1994 – 2018. [On-line serial], Retrieved August 10,2019 from the World Wide Web: http://www.eppo.go.th/index.php/en/en-energystatistics/co2-statistic.

[15] Pollution Control Department (PCD). 2010. Emission Standard Control from Thermal Power Plants. [On-line serial], Retrieved August 20, 2019 from the World Wide Web: http://pcd.go.th/info_serv/reg_std_airsnd03.html#s1.

[16] Office Natural Resources and Environmental Policy and Planning (ONEP). 2012. Environmental Impact Assessment of Thermal Power Plant Report and EIA Process. [On-line serial], Retrieved September 3, 2019 from the World Wide Web: https://eia.onep.go.th/monitor.php?action=y.

[17] Parvez M. and O. Khan. 2019. Parametric simulation of biomass integrated gasification combined cycle (BIGCC) power plant using three different biomass material. *Biomass Conversion and Biorefinery* 10: 803–812.

[18] Parvez M., 2017. Investigation on thermodynamic behavior of apple juice waste- and sugarcane bagasse gasified fuelled combined cycle power generation system. *Biofuels* 11(4): 1-7.

[19] Gambini M., Vellini M., Stilo T., Manno M., and Bellocchi S, 2019. High-efficiency cogeneration systems: The case of the paper industry in Italy. *Energies* 12: 335.

[20] Osueke C., Onokwai A., and Adeoye A, 2015. Energy and exergy analysis of a 75 MW steam power plant in Sapele (NIGERIA). *International Journal of Innovative Research in Advanced Engineering* 2(6).

[21] Eke M.N., Onyejekwe D.C., Iloeje O.C., Ezekwe C.I., and Akpan P.U., 2018. Energy and exergy evaluation of a 220 MW thermal power plant. *Nigerian Journal of Technology* 37(1): 115-123.

[22] Cengle Y.A. and M.A. Boles. 2006. Thermodynamics: an engineering approach, 15th Edition. McGraw-Hill, New York.

[23] Patel T., and D. Patel. 2014. Energy analysis and efficiency assessment of water tube boiler. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)* 11(3): 65-69.

[24] Motokura M., Lee J., Kutani I., and Phoumin H, 2016. Improving emission regulation for coal-fired power plants in ASEAN. ERIA Research Project Report, No.02.

[25] Sosa-Arnao J.H., and S.A. Nebra. 2011. First and second law to analyze the performance of Bagasse boilers. *International Journal of Thermodynamic (IJOT)* 14(2): 51-58.

[26] Department of Industrial Works (DIW). 2018. Guideline to Optimizing the Efficiency of Very Small Biomass Power Plants (VSPP) 2018.Method to Monitor Performance Biomass Power Plants. Department of Industrial Works, Bangkok, Thailand.

[27] Singh O.K., 2019. Exergy analysis of a grid – connected Bagasse-based cogeneration plant of sugar factory and exhaust heat utilization for running a cold storage. *Renewable Energy* 143: 149-163.

[28] North American Insulation Manufacturers Association (NAIMA). 2019. 3E Plus Software for Assessment of Heat Loss Piping and Heat Loss of Wall Boiler. [On-line serial], Retrieved September 15, 2019, from the World Wide Web: https://insulationinstitute.org/tools-resources/.

[29] The U.S. Department of Energy (DOE). 2019. Tool Assessment Performance Steam Turbine. [On-line serial], Retrieved September 20, 2019 from the World Wide Web: https://www4.eere.energy.gov/manufacturing/tech_deployment/amo_steam_tool/.