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Heat Rate Deviation Analysis of a Coal-Fired Power Plant (CFPP) with the Influence of Applicable Coal Prices (ACP)

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ABSTRACT

The assessment of a Coal-Fired Power Plant (CFPP) performance is an intricate process that involves the determination of Heat Rate (HR) deviations of current operational parameters from baseline or target values. This study focuses on HR deviations of a CFPP based on the Applicable Coal Price (ACP), and the influence of the ACP price on daily losses or gains are thoroughly analyzed for key performance parameters for three fixed ACP of RM12, 18, and 24 per GJ. This paper mainly investigates key parameters and related equipment that significantly affect the HR of the CFPP and ranks the parameters affecting HR from most significant to least significant. The baseline or target values are obtained from the plant commissioning manuals and the Performance Guarantee Test (PGT). Actual real-life operational data from a 700MWn CFPP is utilized to improve the accuracy and confidence levels of the results obtained. It was found that at the nominal operating baseload, the most significant negative HR deviation is for the Rotary Air Heater (RAH) gas exit temperature with a negative HR deviation of -137.9 kJ/kWh leading to an annual loss of RM17.6 million at ACP of RM24/GJ while the superheater and reheater spray flows are contributing least to the HR deviation. This analysis highlighting the impact of key parameters affecting the performance enables plant operations and maintenance teams to focus on such parameters to mitigate losses.

Keywords: Applicable coal price, coal-fired power plant performance, heat rate deviation analysis, heat rate

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INTRODUCTION

Coal Fired Power Plants (CFPP) are the key pillar of support for Malaysia's power generation sector, providing close to 40% of the national energy demand up to 2030 (Energy Commission of Malaysia, 2020). In a rapidly growing economy for a developing country, CFPPs are operated on baseload mode, which means the plant produces power at almost full capacity throughout the day to meet the country's energy demands. Any negative deviation in the Heat Rate (HR) for base loads plants will significantly affect the plant performance. The HR of a CFPP is defined as the amount of energy consumed by an electrical generator to produce one unit of electricity in Kilowatt Hours (kWh), and the HR deviation refers to a positive or negative change in the HR against a baseline value. As such, CFPP needs to operate at its optimum efficiency to reduce the cost of fuel used, which will translate into a lower cost of producing energy to maintain the plant's sustainability and profitability for the country's well-being (Zhang et al., 2018).

Plant personnel and managers must be aware of the HR deviation of the plant to ensure the plant is operating at its optimum performance. The main focus of this investigation is to conduct an HR deviation analysis which can assist plant operators in better understanding the effect of parameter deviations on the HR of the plant and thus take the appropriate action to improve the performance of the plant. The HR deviations analysis can provide key indicators of how well the plant is performing daily or where the operations and maintenance personnel need to work on improving the plant's performance. Actual real-life operational data from a 700 MW CFPP is utilized in this study. The plant has been operating for almost 20 years, so relevant data from the commissioning and Performance Guarantee Test (PGT) are available. Moreover, there are three identical units of 700MW; therefore, the analysis applies to all three units.

Scholars in several previous studies have investigated the performance of CFPP. However, most past research work has only focused on obtaining the overall heat rate of CFPP without focusing on key operational performance indicators of the plant, while this study focuses on the key operational performance indicators of the CFPP. Furthermore, most previous studies have not conducted a financial analysis of the plant, which is vital for plant operators to determine the profitability of the plant based on the current operating regime, while this study correlates key plant performance indicators with economic analysis (Ahmadi & Toghraie, 2016; Elhelw et al., 2019; Sabzpooshani et al., 2019). Moreover, the impact of the Applicable Coal Price (ACP) on the HR deviation of the plant has not been investigated in previous research work, whereas this investigation focuses on the impact of ACP on key plant performance parameters (Devandrin et al., 2016; Almedilla et al., 2018; Oyedepo et al., 2020). In addition, most previously investigated units have a design capacity below 500MWn, while the present study focuses on 700MWn units (Neshumayev et al., 2018; Wijaya & Widodo, 2018).

With the increasing prices of ACP, and the price of coal, the primary fuel source for a CFPP, it is of utmost importance to consider the effect of coal prices and their effect on plant performance. While several studies have investigated certain parameters of the boiler operations, in terms of daily operations, there is nothing much which can be done to monitor and mitigate the issues as the recommendations require the unit to be on outage for maintenance (Gupta & Kumar, 2015; Pachaiyappan & Prakash, 2015). In addition, while there have been previous studies on intelligent boiler maintenance techniques in boiler trips, such studies did not focus on the performance of CFPP (Nistah et al., 2014). Therefore, the present study analyses key areas of CFPP performance where the operations team can address the gaps or negative deviations of plant HR as the analysis can highlight key areas of concern that significantly affect plant performance. Furthermore, it is not feasible to focus on certain areas of CFPP performance that require unit outage as there will be monetary losses when the unit is not producing load; therefore, the present study focuses on areas such as the feedwater heaters, condenser, and overall key parameters which may be addressed operationally without the need of waiting for outage (Braun, 2021).

The main objective of this paper is to investigate HR deviations of a CFPP based on the ACP, and the impact of ACP prices on the daily losses or gains to the plants are thoroughly analyzed for key performance indicators. There are three ACP prices considered in this study, which are RM12, 18, and 24 per GJ, and these three ACP prices reflect the transition of ACP from RM12 from the past five years to the higher ACP of RM24 due to increasing global coal prices (Energy Commission of Malaysia, 2022). Currently, the coal price, or ACP, is Ringgit Malaysia (RM) 24/GJ, equivalent to RM482 per ton for coal with a gross calorific value of 4800 kcal/kg. Therefore, plant personnel needs to understand the more significant impact on gains or losses based on ACP so that more attention may be given to key parameters that might adversely affect the plant HR causing monetary losses. The process of monitoring HR deviation involves utilizing several rules of thumb and key information from the plant commissioning manuals. Several intricate details may also be obtained from the commissioning test runs and the Performance Guarantee Test (PGT), which contains crucial operating parameters of the plant at 100% Turbine Maximum Continuous Rating (TMCR). The parameters obtained from the PGT form the guiding principles of having a robust monitoring regime of the plant as the plant is considered to be operating at its best during the Performance Guarantee Test. Furthermore, several correction curves for key operational parameters are also provided in the PGT, which may be incorporated into the HR deviation monitoring. The CFPP operational data is obtained from the Plant Information (PI) Data Link, which enables the extraction of data from the PI Server linked to the Distributed Control System (DCS), a platform for controlling the plant operations and storing operational data of the CFPP. The usage of actual plant data increases the confidence levels in the outcomes of the study.

It is vital to monitor which parameters are most influential towards the performance of the plant. Thus, such parameters would be categorized as high-priority parameters to be monitored by the operations teams. The constant monitoring and tracking of key parameters would ensure the plant operates optimally. Although the other parameters may be less influential towards plant performance, it is still important to monitor parameters such as the feedwater heaters' Terminal Temperature Difference (TTD) and Drain Cooler Approach (DCA) which are able to provide insights on the correct operating regime of the feedwater heaters, for instance, any abnormalities in the heater level may be obtained from the TTD and DCA results. Such abnormal levels of FWH may lead to overfiring in the boiler and damage the boiler and FWH tubes. Furthermore, incorrect valve lineups around the FWH, such as vent valves, may also be detected through FWH performance monitoring. The health status of the Low-Pressure Heaters (LPH) and High-Pressure Heaters (HPH) feedwaters are vital for maintenance teams, especially before an upcoming outage. This valuable information ensures that the heaters not performing as per the PGT targets may be rectified during the outage. The overall HR deviation due to deviation in TTD is also highlighted and discussed in the proceeding sections.

The condenser TTD and a few other key parameters deviations are able to provide valuable information such as the cleanliness of the water box, the heat load to the condenser by means of cooling water temperature rise, and also the possibility of air ingress due to increases in dissolved oxygen at the Condensate Extraction Pump (CEP) which requires valve line up. The HR deviation caused by variation of backpressure due to cooling water flow is also discussed in the proceeding sections.

The HR deviation can also provide vital information for the maintenance teams to prioritize maintenance activities affecting the plant's performance. Once an HR deviation has been detected by operations personnel, the issue is rectified based on the operations manuals, and if the issue is not resolved, only then the maintenance teams are involved. Such information is valuable in the ever-changing power generation sector, where plants cannot go for regular shutdowns due to the unavailability of planned outages or grid constraints. Longer downtimes are undesirable as the plants' availability factor and finances are adversely affected. Therefore, by early detection and identification of parameters and equipment that adversely affect plant performance, the maintenance team can rectify the issues quickly with proper planning due to early detection based on continuous HR deviation monitoring.

The magnitude of HR deviation changes with the coal prices, known as Applicable Coal Price (ACP), which is quoted in RM/GJ and changes quarterly. In Malaysia, the ACP is regulated by the Energy Commission (EC), and the power plant management is informed of the upcoming new ACP (Energy Commission of Malaysia, 2022). The ACP is affected by changes in coal pricing due to market demand and supply factors. However, it should be noted that the plant management has no authority to influence the ACP other than buying coal when the coal price is low and delaying coal shipments when the coal pricing is higher, although the storage yard and ship handling capabilities may hinder such a move. Thus, during the higher ACP periods, it is even more crucial for plant operators to focus more on managing the plant at optimum efficiency by frequently monitoring the HR deviation to minimize any potential losses caused by operational parameter deviations.

Background and CFPP Operations

The CFPP under investigation operates at baseload, where the plant produces maximum power output continuously based on the Contractual Available Capacity (CAC), which is the maximum power the plant produces based on the contractual agreement. Therefore, deviations in key parameters cause significant HR deviations leading to greater monetary losses during higher ACP periods. The overall CFPP prosses are illustrated in Figure 1, and Table 1 contains the necessary nomenclature. The cycle begins from the condenser, where demineralized water, which is raw water treated to meet plant requirements, is pumped by the Condensate Extraction Pump (CEP) through the LPHs before reaching the deaerator and the LPH is responsible for preheating the condensate before it enters the deaerator (Bisercic & Bugaric, 2021).

From the deaerator, the operating fluid, now called feedwater, is pumped through the series of HPH by the Boiler Feed Pumps (BFP) before entering the economizer inlet of the boiler. Similar to the LPH, the function of the HPH is to preheat the feedwater using

Table 1
Nomenclature for CFPP process flow as shown in Figure 1

Item	Description
HP Turbine	High-pressure turbine
IP Turbine	Intermediate pressure turbine
IP Exhaust	Exhaust flow from IP turbine to LP turbine
LP1/LP2 Turbine	Low pressure 1,2 turbine
LP Exhaust	Exhaust flow from LP turbine to condenser
CEP	Condensate extraction pump
LPH3,4	Low-pressure heater 3,4
BFP	Boiler feed pump
HPH6,7,8	High-pressure heater 6,7,8
$T_{FurnOut}$	Furnace outlet temperature
T_{RAHOut}	Rotary air heater gas outlet temperature
m_{RHS}	Mass flow of reheater spray flow
m_{SHS}	Mass flow of superheater (attemperator) spray flow
m_{excLPH}	Excess flow of water in the LPH (cycle in dotted lines)
m_{excHPH}	Excess flow of water in the LPH (cycle in dotted lines)

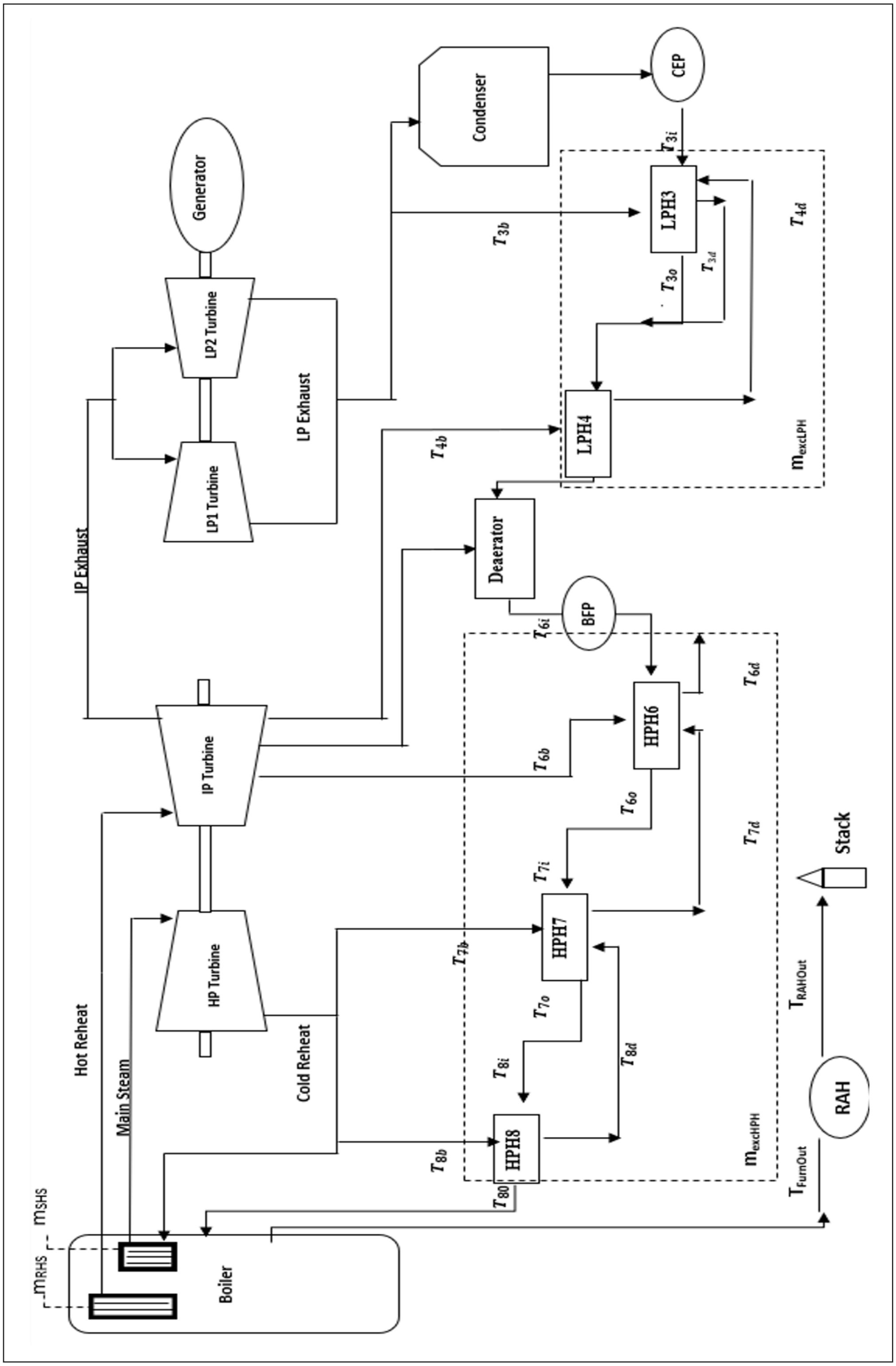

Figure 1. CFPP process flow

extraction steam from various stages of the turbine (Buckshumiyanm & Sabarish, 2017). From the economizer inlet, the operating fluid circulates to the boiler drum and through the downcomers before rising through the water walls of the boiler before re-entering the boiler drum, and a portion of the operating fluid is converted into vapor in this process (Mohammed et al., 2020). The boiler drum separates vapor from the liquid, which is then channeled to the superheaters, after which the superheater steam enters the HP Turbine, rotating the shaft coupled to the electrical generator where conversion of mechanical rotational energy to electrical energy takes place, producing energy (Tian et al., 2017). After expansion in the high-pressure turbine, the exhaust steam renters the boiler before being reheated in the reheater before entering the intermediate pressure turbine as hot reheat steam. The exhaust steam from the intermediate-pressure turbine enters the lower-pressure turbine, and the exhaust of the low-pressure turbine is condensed in the condenser while the cycle is completed when the condensate is circulated through the CEP (Behbahaninia et al., 2017; Wang et al., 2019).

METHODOLOGY

In order to determine the impact of various aspects influencing the HR of the CFPP, it is crucial to determine the HR deviation of the plant. Various parameters may influence the plant's performance, such as main steam temperature, hot reheat temperature, main steam pressure, feed water temperature, and Rotary Air Heater (RAH) outlet temperature. The deviation of the parameter is calculated by obtaining the difference between the present value from the baseline value, which is usually the operational design value or a value based on the present load of the plant.

Therefore, it is possible to obtain both positive and negative HR deviations. The focus is on negative HR deviation, which leads to operational losses, as positive HR deviation indicates gains in operational performance. It is important to note that while positive HR deviation is beneficial, there may be other restraints, for instance, the maximum allowable temperature of the piping in which the medium, such as main steam, flows. Thus, it is desirable to operate at the optimum temperature and pressure. The quantification of the HR deviation is beneficial to identify the key areas contributing to plant losses.

Several factors can influence the significance of HR deviation financially, such as the Fuel Cost (FC) in RM/GJ, the price of coal, the unit's Capacity Factor (CF), and the load generated. In general, the HR deviation for each operational parameter may be determined based on the average figure for several hours, usually by the notation of shifts, which refers to the block of time where one team of operators manage the plant before handing it over to the next team of operators in the following shift. Therefore, monitoring the HR deviation on a shift-per-shift basis is advisable for easy tracking and monitoring. At the same time, this can instill a spirit of responsibility among plant operators to ensure they always operate the plant at optimum efficiency and report any major deviations to the senior operations personnel and maintenance teams.

Parameter deviation is the difference between the actual value of the parameter and the reference or baseline value of the parameter, as illustrated in Equation 1:

$$\text{Parameter Deviation} = \text{Parameter}_{\text{Actual}} - \text{Parameter}_{\text{Reference}} \quad [1]$$

The heat rate deviation is evaluated using the following relationship as shown in Equation 2, where the HR factor is defined as the fixed change in HR for the parameter, and the HR Factor change refers to the fixed change in the parameter's value:

$$\text{Heat Rate Deviation} = \frac{\text{Parameter Deviation x HR Factor}}{\text{HR Factor change}} \quad [2]$$

The total losses or gain in a day in Ringgit Malaysia (RM) are determined using Equation 3, where the HR deviation is obtained using Equation 2, the Net Energy Output (NEO) is the total net power generated per day while the ACP is the applicable coal price utilized:

$$\text{Losses or Gain in RM per day} = \frac{\text{HR Deviation } (\frac{\text{kJ}}{\text{kWh}}) \text{ x NEO (MWh) x ACP } (\frac{\text{RM}}{\text{GJ}})}{1000} \quad [3]$$

The available data from the plant Distributed Control System (DCS), which is linked to the Plant Information (PI) server, is extracted and shown in a simplified form in Table 2**,** and this input data is utilized to analyze the HR deviation. The measuring points or locations of the items listed in Table 2 are included in Figure 1.

Table 2
Pressures and temperatures of key parameters at load 729 MWg, including nomenclature

Item	Nomenclature	Unit	Parameter
Main steam temperature	T_{MS}	°C	532
Main steam pressure	P_{MS}	bar	530
Hot reheat steam temperature	T_{HRH}	°C	166
Superheater attemperator spray flow	$\dot{m}_{SHS}$	t/h	3.5
Reheater attemperator spray flow	$\dot{m}_{RHS}$	t/h	0.90
Rotary air heater outlet gas temp	T_{RAHOut}	°C	190
Furnace outlet gas temp	$T_{FurnOut}$	°C	382
Excess water flows through LP heaters	$\dot{m}_{excLPH}$	%	2.55
Excess water flows through HP heaters	$\dot{m}_{excHPH}$	%	2.28
Economizer inlet temp	T_{EcoIn}	°C	265
Condenser vacuum	$P_{condvac}$	mbar-A	92

Feedwater Heaters

There are several specific performance indicators for Feedwater Heaters (FWH), such as the Terminal Temperature Difference (TTD), Drain Cooler Approach (DCA), and Temperature Rise (TR) of LPH and HPH, which may be monitored regularly. During normal operations, the TTD and TR can provide quick guidelines on whether the heater is operating at a normal level or otherwise for operators to respond swiftly to mitigate any changes in the FWH operating parameters. It is especially important to monitor the deviations of these parameters before the unit goes for planned maintenance work to ensure the defects may be rectified. The necessary cleaning works of the feedwater heaters using appropriate chemicals may also be done during an outage. The baseline values of the TTD, DCA, and TR, obtained from the Performance Guarantee Test (PGT) and Heat Balance Diagram (HBD), are shown in Table 3, and a general outline of an FWH is illustrated in Figure 2.

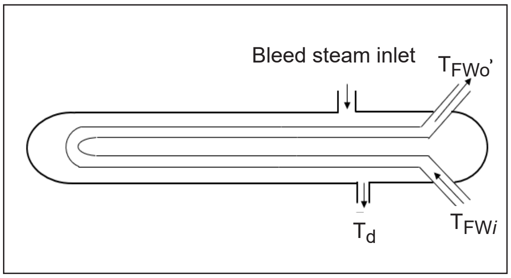

Figure 2. Feedwater heater arrangement

Table 3
FWH TTD, DCA and TR baseline target values

LPH/HPH	Baseline Target Values		
	Terminal Temperature Difference (TTD)	Drain Cooler Approach (DCA)	**Temperature Rise (TR)**
LPH3	3.00	-	**17.8**
LPH4	3.00	-	**37.2**
HPH6	-2.00	3	**30.9**
HPH7	-1.00	3	**37.7**
HPH8	-1.50	3	**18.8**

The terminal temperature difference is the difference between the feedwater outlet temperature and the saturated temperature at the shell pressure as illustrated in Equation 4 and Equations 4 to 6 have been adapted from Devandrin et al. (2016):

$$\text{Terminal Temperature Difference(TTD)} = \text{Feedwater Temperature Out(To)} - T_{\text{Sat@Shell Pressure}} \quad [4]$$

The drain cooler approach is the difference between the drain temperature of the feedwater heater and the feedwater inlet temperature, as shown in Equation 5:

$$\text{Drain Cooler Approach (DCA)} = \text{Drain Temperature}(T_d) - \text{Feedwater Temperature In}(T_i) \quad [5]$$

The temperature rise (TR) is the difference between the feedwater outlet temperature and inlet temperature, as shown in Equation 6:

$$\text{Temperature Rise (TR)} = \text{Feedwater Temperature Out } (T_o) - \text{Feedwater Temperature In}(T_i) \quad [6]$$

The available data from the plant DCS, which is linked to the PI server, is extracted and shown in a simplified form in Table 4, and this input data is utilized to analyze the HR deviation.

Table 4
FWH parameters temperature at load 729 MWg, including nomenclature

Item	Nomenclature	Parameter (°C)
A) Feed water		
HPH6 Inlet	T_{6i}	188.4
HPH6 Outlet	T_{6o}	216.2
HPH7 Inlet	T_{7i}	216.2
HPH7 Outlet	T_{7o}	249.6
HP8 Inlet	T_{8i}	246.5
HPH8 Outlet	T_{8o}	266.9
B) Drains		
HPH6	T_{6d}	190.6
HPH 7	T_{7d}	214.7
HPH 8	T_{8d}	250.5
C) Saturated temperature		
HPH8	T_{HP8sat}	265.5
HPH 7	T_{HP7sat}	244.1
HPH 6	T_{HP6sat}	209.1
LPH 4	T_{HP4sat}	140.29
LPH 3	T_{HP3sat}	109.46
D) Condensate		
LPH3 Inlet	T_{3i}	86.3
LPH3 Outlet	T_{3o}	104.2
LPH4 Inlet	T_{4i}	104.3
LPH4 Outlet	T_{4o}	145.7

Condenser

The main function of the condenser is to convert exhaust steam from the LPT to liquid water, which can be pumped back to the boiler. It is vital to monitor the key parameters affecting the condenser's performance. Furthermore, several underlying issues, such as condenser water box cleanliness, may be obtained from the condenser performance monitoring regime. The general outline of a condenser is shown in Figure 3.

The terminal Temperature Difference (TTD) is the difference between saturated temperature obtained at condenser pressure and the cooling water outlet temperature, as shown in Equation 7 and Equations 7 to 10 have been adapted from Sikarwar et al. (2013):

$$\text{Terminal Temperature Difference (TTD)} = T_{\text{Sat@Condenser Pressure}} - \text{CWOutletTemp} \quad [7]$$

The variation due to Cooling Water (CW) flow is the difference between backpressure due to CW flow and target backpressure at the cooling water inlet, as illustrated in Equation 8:

$$\text{Variation due to CW Flow} = \text{Back Pressure due to CW Flow} - \text{Target back pressure at CW inlet} \quad [8]$$

The variation due to air ingress or dirty tubes is the difference between actual condenser pressure and backpressure due to Cooling Water (CW) flow, as illustrated in Equation 9:

$$\text{Variation due to air ingress or dirty tubes} = \text{Actual Condeser pres} - \text{Backpres due to CW Flow} \quad [9]$$

The variation from the target is the difference between actual condenser pressure and target backpressure due to Cooling Water (CW) inlet temperature, as shown in Equation 10:

$$\text{Variation from target} = \text{Actual condenser pres} - \text{Target back pres at CW Inlet temp} \quad [10]$$

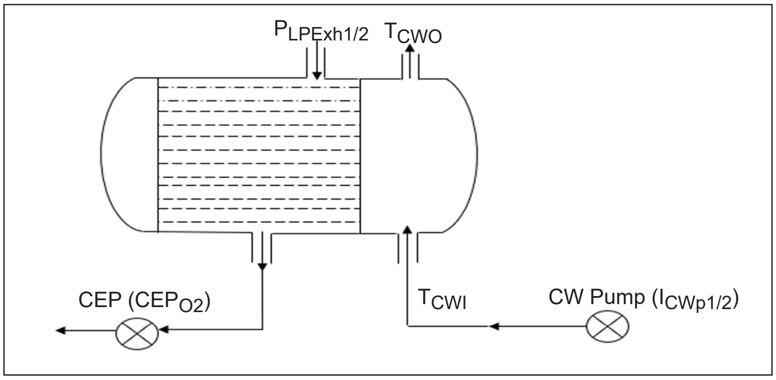

Figure 3. Condenser arrangement

The available data from the plant DCS, which is linked to the PI server, is extracted and shown in a simplified form in Table 5, and this input data is utilized to analyze the HR deviation. The measuring points or locations of items listed in Table 5 are included in Figure 3.

Table 5
Condenser parameters pressures, temperature and enthalpy at load 729 MWg including nomenclature

Item	Nomenclature	Unit	Parameter
CW inlet temperature	T_{CWi}	°C	29.96
CW outlet temperature	T_{CWo}	°C	38.22
CW Temperature rise	T_{CWTR}	°C	8.26
CEP discharge oxygen	CEP_{02}	%	4.47
CW Pump1 Motor current	I_{CWP1}	A	183.39
CW Pump2 Motor current	I_{CWP2}	A	179.50
LP1 Exhaust pressure	P_{LPExh1}	mbar-A	86.22
LP2 Exhaust pressure	P_{LPExh2}	mbar-A	79.43
Condenser pressure	$P_{Condpres}$	mbar-A	74.57
Saturated Temperature at Condenser Pressure	$T_{SatCond}$	°C	40.18
Condenser vacuum	$P_{Condvac}$	mbar-A	79.15

RESULTS AND DISCUSSION

Monitoring and analyzing deviations in key parameters affecting the HR deviation is vital for plant operators to ensure the unit is operating at optimal performance. From the HR deviation results, the operators can identify areas requiring intervention, thus mitigating the negative HR parameters. The HR deviation is also able to provide an indicator of underlying issues in the unit. The increase in the ACP causes an increase in the daily loss; thus, with the rising price of coal, it is of utmost importance for the plant operators to ensure the unit operates with minimal negative HR deviation.

The heat rate of CFPP is significantly affected by several key parameters, as shown in Table 6. The main steam temperature, which is the temperature at which the steam leaves the final superheater outlet and enters the High-Pressure Turbine (HPT), is one of the key indicators of the plant's performance. A drop in the main steam temperature will negatively impact the HR. This study shows that an 8°C drop in the main steam temperature from the baseline target temperature leads to an HR increase of 24.3 kJ/kWh, which causes a monetary loss of RM 8,504 per day at the current ACP of RM 24/GJ. The drop in the main steam temperature suggests possible issues with the combustion, such as inadequate firing, which does not supply enough heat to the superheaters to achieve the main steam temperature, or poor cleanliness of the superheater due to slagging, which causes the inability of steam to absorb heat from the flue gas path. One of the possible remedies is conducting selective soot blowing at the superheater area or changing to a different type of coal to address the issue.

The Hot Reheat temperature, the steam flow from the HPT exhaust that has gone through a reheating process in the boiler's reheater section, is also an important indicator of plant performance. A drop in the hot reheat steam temperature will negatively affect the HR of the plant, such as the 10°C drop in hot reheater steam temperature in this study leads to an increase in the HR by 24.5 kJ/kWh leading to a daily monetary loss of RM 8,587 per day. As previously discussed in the context of the main steam temperature, there are many possible reasons, such as poor cleanliness of the reheater surface, which causes poor heat absorption and, thus, the inability of steam to absorb heat. The possible remedies for lower hot reheat steam include conducting selective soot blowing at the rear pass of the boiler and increasing the gas recirculation damper opening if the plant is equipped with the gas recirculation system to enable more heat to be recirculated to the furnace from the tapping after the rotary air heater.

The superheater and reheater attemperator spray flows serve as a control measure to ensure the main steam and hot reheat temperatures do not exceed the setpoint temperature, as higher temperatures can damage boiler tubes and turbine blades while initiating the Boiler Protection system to trip the boiler if the main steam and hot reheat temperatures are too high. Typically, there is an expected superheater spray flow value of 2.68% of the main steam flow to maintain the nominal main steam temperature. Suppose the superheater spray flow increases above the expected flow. In that case, there is a negative effect on the HR, such as the increase in superheater spray by 0.82% from the baseline value of 2.68% leads to an increase in HR by 2.6 kJ/kWh, causing a daily monetary loss of RM 820 at an ACP of RM 24/GJ as illustrated in Table 6. Furthermore, this indicates the possibility of overfiring in the boiler as more heat is absorbed in the superheater; thus, the main steam requires cooling to protect the tubes obtained from the superheater spray. The typically expected flow for the reheater spray is 0%, and an increase in reheater spray indicates a negative effect on the HR. In this typical scenario, as shown in Table 6, the reheater outlet steam temperature is lower than the reference value; thus, logically, there should be no spray flow to cool down the reheater outlet steam, but since there is a spray flow of 0.9%, which leads to increase of HR by 15.8 kJ/kWh causing daily monetary losses of RM 5,527 at an ACP of RM 24/GJ, this suggests the reheater spray flow valve is passing, or there are issues in the control logic.

The furnace flue gas outlet temperature and the rotary air heater outlet temperature are major indicators of boiler performance, cleanliness, and air heater performance. Generally, an increase in the furnace flue gas outlet temperature indicates poor heat absorption from the flue gas to the boiler water walls, superheater, and reheater elements. An increase in the furnace flue gas outlet temperature negatively affects the HR, such as the increase of furnace outlet flue gas temperature of 32^{o}C which leads to an increase in HR by 80.9 kJ/kWh, causing a daily monetary loss of RM 28,344 at an ACP of RM 24/GJ since there is a wastage of heat which is not absorbed in the furnace water walls or elements. The rotary air heater outlet temperature is a significant indicator of the rotary air heater's performance. An increase in the rotary air heater outlet temperature also negatively affects the HR, such as the increase in rotary air heater outlet temperature of 30^{o}C causing an increase in HR of 137.9 kJ/kWh, which leads to a daily monetary loss of RM 48,314 at an ACP of RM 24/GJ, while this condition indicates there is possible chock age in the air heater elements which is causing poorer heat transfer from the hot end to the cold end of the air heater. Furthermore, a chock age in the air heater would cause a buildup of hot flue gas in the furnace outlet, as seen in this scenario. It reduces the velocity of the flue gas exiting the furnace, thus increasing the chances of the formation of fouling on the rear pass of the boiler, causing poorer heat absorption. The remedy to this situation is to improve the performance of the air heater by clearing the chock age, which may be done by performing high-pressure water washing during a unit outage or conducting soot blowing at lower operating loads as the enthalpy of the steam is higher thus dry steam is utilized to clean the air heater elements. If soot blowing is conducted at higher loads, the air heater soot blower will have lower enthalpy steam which means there will be wet steam; thus, the chock age in the elements will become worse instead of improving. In short, as highlighted by (Sundaravinayaka & Jayapaul, 2017), while several RAH improvements may be achieved by offline cleaning, several actions may be taken by the operator to mitigate the issue as discussed, such as effective soot blowing and other operational adjustments, such as air-fuel ratio, changing of coal type as temporary mitigation if the situation permits and so forth.

The condenser vacuum is another key indicator of plant performance. The condenser is an important element of the turbine cycle which is responsible for fulfilling the heat rejection criteria of the Rankine cycle. The cooling water absorbs the rejected heat, and it is crucial to maintain the condenser vacuum at the nominal value to ensure the plant's performance is not adversely affected. An increase in the condenser vacuum negatively affects the HR of the plant, such as the increase in condenser vacuum of 7 mbar-A, which increases the HR by 38.2 kJ/kWh leading to a daily monetary loss RM 13,391 at an ACP of RM 24/GJ. This trend has also been seen by Gupta and Kumar (2015).

The economizer inlet temperature is an important indicator of the overall feedwater heaters' performance, as the feedwater heaters are responsible for preheating the feedwater before it enters the boiler. A drop in the economizer inlet temperature affects the heat rate negatively, such as the drop in economizer inlet temperature of 6^{o}C causes an increase in the HR by 24.3 kJ/kWh, leading to a daily monetary loss of RM 8,503 at an ACP of RM 24/GJ since the boiler requires more heat input to achieve the desired main steam and reheat steam temperatures. A lower economizer inlet temperature also generally indicates the feedwater heater train's poor performance, as Devandiran et al. (2016) described.

The daily monetary losses or gains are greatly impacted by the change in ACP price, as seen in Table 6. As the ACP increases from RM 12/GJ to RM 18/GJ and subsequently to the present ACP of RM 24/GJ, the magnitude of daily losses increases for all the key parameters for the same HR change. For instance, the daily losses for a drop in main steam temperature by 8^{o}C increase from RM 4,252 to RM 8,504 as the ACP increase from RM 12/GJ to RM 24/GJ. It highlights the significant impact of the ACP prices towards the monetary gains or losses of the CFPP, and in the situation where the coal price, or in other words, the ACP, increases, it is even more vital for plant operators to pay more attention and to remedy such key parameters which are causing negative HR deviation to minimize the monetary losses.

The ranking of key parameters which are causing the most monetary losses to the least monetary losses based on the analysis of which parameter affects the HR deviation negatively the most is shown in Figure 4. The RAH Outlet temperature has the highest contribution to the HR deviation of the CFPP. The monetary losses of RM 17.6 million per year are for the increase of the RAH outlet temperature alone. The second parameter which affects the HR deviation the most is the furnace outlet temperature, which is closely related to the RAH outlet temperature, as previously discussed. Thus, if the RAH chock age may be improved, the potential for improvement in plant performance is very significant as it will address losses due to RAH outlet temperature and furnace outlet temperature. The other

Table 6
CFPP heat rate impact factor based on parameter

No	Parameter	Nomenclature	Reference value	Actual	Deviation	Heat Rate Factor		Losses/Gain (RM/day)			
						Change in parameter	HR (kJ/kWh)	HR change (kJ/kWh)	ACP: RM12/GJ	ACP: RM18/GJ	ACP: RM24/GJ
1	Main steam temperature	T_{MS}	540.00	532	-8	10.00	-30.34	24.3	-4252	-6378	-8504
2	Hot reheat steam temperature	T_{HRH}	540.00	530	-10	10.00	-25.28	24.5	-4294	-6441	-8587
3	Main steam pressure	P_{MS}	170.00	166	-4	0.70	-4.05	23.1	-4054	-6082	-8109
4	Superheater spray	$\dot{m}_{SHS}$	2.68	3.5	0.82	0.82	2.63	2.6	-460	-690	-920
5	Reheater spray	$\dot{m}_{RHS}$	0.00	0.9	0.9	1.50	26.29	15.8	-2763	-4145	-5527
6	Rotary air heater outlet temperature	T_{RAHOut}	160.00	190	30	5.50	25.28	137.9	-24157	-36235	-48314
7	Furnace outlet temperature	$T_{FurnOut}$	350.00	382	32	10.00	25.28	80.9	-14172	-21258	-28344
8	Excess water flows through LPH	$\dot{m}_{excLPH}$	0.00	2.55	2.55	5.00	101.12	51.6	-9042	-13563	-18084
9	Excess water flows through HPH	$\dot{m}_{excHPH}$	0.00	2.28	2.28	5.50	101.12	41.9	-7345	-11018	-14690
10	Economizer inlet temperature	T_{EcoIn}	271.00	265	-6	2.50	-10.11	24.3	-4252	-6377	-8503
11	Condenser vacuum	$P_{condvac}$	85.00	92	7	10.00	54.60	38.2	-6696	-10044	-13391

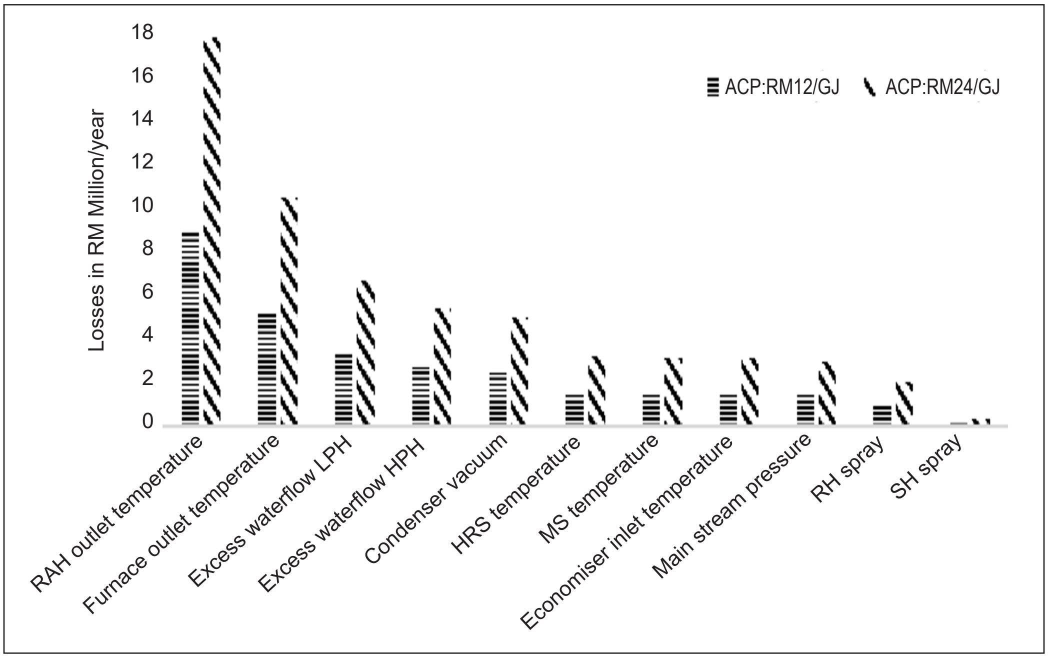

Figure 4. HR deviation losses for key parameters

significant cause for losses due to the excess water flow in the LPH is caused by the higher make of the flow. Thus, the losses due to excess water flow through LPH may be reduced by attending to passing valves, such as drain valves, to reduce the makeup flow. The excess flow of HPH is due to the feedwater flow being higher than the main steam flow, and this also contributed to passing drain and vent valves along the feedwater lines, which must be rectified to reduce this loss. The condenser vacuum is also a significant contributor to the losses, and the performance of the condenser may be improved by addressing potential air ingress and blockage in the cooling water inlet at the water box. The superheater and reheater spray flow contribute the least to the HR deviation.

Feedwater Heaters

The performance of the feedwater heaters is an important aspect of the turbine cycle of a CFPP, which serves the purpose of preheating condensate in the case of LPH and preheating feedwater in the case of HPH preheating feedwater. The extraction steam from various stages of the High Pressure, Intermediate Pressure, and Low-Pressure Turbines is used to preheat the fluid medium passing through the feedwater heater to a higher temperature so that the boiler has to consume less heat energy in the form of coal to achieve the main steam and reheat steam temperatures.

Thus, it is vital to ensure that the FWHs are consistently performing at the optimum performance. The three key performance parameters associated with FWH performance are the Terminal Temperature Difference (TTD), Temperature Rise (TR), and Drain Cooler Approach (DCA). The nominal values of these key parameters are readily available in the plant Heat Balance Diagram (HBD) or may be taken from the Performance Guarantee Test (PGT).

Based on Table 7, the current values of the TTD are compared with the baseline or reference values obtained from the HBD or PGT. The TTD is an indicator of the FWH's performance in terms of heat transfer. An increase in the TTD value indicates an increase in heat transfer. The TTD for HPH8, 7, and 6 are negative 4.21^{o}C, 5.40^{o}C, and 6.97^{o}C, respectively, while the TTD for LPH 4 and 3 are positive 3.49^{o}C and 5.30^{o}C, respectively. However, it is crucial to ensure the TTD is maintained at the nominal range and does not decrease too much, as it can negatively affect the overall performance of the Turbine Cycles.

The HPH8 has the highest deviation from the design value and combined with a significant HR factor, the daily monetary losses for HPH8 causes are the most significant, RM3,844 per day compared to HPH7 and HPH6, which are contributing to daily monetary losses of RM1,869 and RM2,110 respectively for an ACP of RM 24/GJ. As previously discussed, the daily monetary losses increase as the ACP increases from RM 12/GJ to RM 24/GJ. For instance, for HPH8, the daily losses increase from RM1,922 to RM3,844 as the ACP increases from RM12/GJ to RM 24/GJ. The TTD for the LPH is around the nominal range; thus, the HR deviation may be considered insignificant, although continuous monitoring is necessary to detect any changes in the LPH performance over time. In terms

Table 7
FWH performance parameters

No	Parameter	Reference value (^{o}C)	Actual (^{o}C)	Deviation (^{o}C)	Heat Rate Factor		Daily Gain/Losses (RM/day)		
					Change	HR (kJ/kWh)	ACP: RM12/GJ	ACP: RM18/GJ	ACP: RM24/GJ
1	HPH8 TTD	-1.5°C	-4.21	2.71	2.50	10.1	-1922	-2883	-3844
2	HPH7 TTD	-1.0°C	-5.40	4.40	2.50	3.03	-935	-1402	-1869
3	HPH6 TTD	-2.0°C	-6.97	4.97	2.50	3.03	-1055	-1583	-2110
4	LPH4 TTD	3.0°C	3.49	0.49	2.50	3.03	-104	-155	-207
5	LPH3 TTD	3.0°C	5.30	2.30	2.50	3.03	-489	-733	-977
6	HPH8 TR	18.8	20.34	1.54	-	-	-	-	-
7	HPH7 TR	37.7	33.46	-4.24	-	-	-	-	-
8	HPH6 TR	30.9	27.76	-3.14	-	-	-	-	-
9	LPH4 TR	37.2	41.64	4.44	-	-	-	-	-
10	LPH3 TR	17.8	17.31	-0.49	-	-	-	-	-
11	HPH8 DCA	3	3.96	0.96	-	-	-	-	-
12	HPH7 DCA	3	-1.52	-4.52	-	-	-	-	-
13	HPH6 DCA	3	2.17	-0.83	-	-	-	-	-

of the DCA, the DCA may only be calculated for HPH 6,7 and 8 as the measurements needed to evaluate the DCA are available for these heaters since the heater drain temperature instrument is not installed in the LPHs. The DCA needs to be maintained around the nominal range to prevent flashing in the drain cooler section, which may cause damage to the heater tubes. It is observed that the DCA for HPH 6 and HPH8, 2.17^{o}C and 3.96^{o}C, respectively, are within normal range while the DCA for HP7, -1.52^{o}C, is negative instead of positive, which indicates possible issues with the level control of the heater as the heater level may have increased causing the decrease of DCA. A decrease in DCA alongside a decrease in the TR indicates the heater level increase, as seen in HPH7. An increase in the FWH level causes overfiring in the boiler, which increases fuel consumption and causes other associated issues, such as an increase in furnace outlet temperature, an increase in superheater and reheater spray flows, and damage to boiler tubes and FWH tubes. Although (Almedilla et al., 2018) have investigated the procedure of determining the TTD of FWH, there is no correlation between the deviation of TTD with financial analysis and data utilized from smaller 135 MWn CFPP.

Condenser

The condenser performance monitoring is carried out by monitoring several key parameters around the condenser. The input parameters from the DCS are illustrated in Table 4, and the output of the analysis conducted is summarized in Table 8. There are three data sets that refer to the data taken from the DCS for three days at similar unit loads and at the same time to ensure fair comparison at similar sea tide levels. In general, the first parameter which is observed is the Cooling Water (CW) temperature rise. The actual CW temperature rise is compared with the expected CW temperature rise at design condition, and it is seen that the CW temperature rise has increased by approximately 1^{o}C, which suggests the amount of rejected heat into the condenser has increased and thus, the condenser duty has increased, causing poor condenser performance. The actual condenser TTD is much lower than the expected TTD at design conditions, which suggests the condenser has better heat transfer than expected. The CEP discharge oxygen levels indicate any possible air ingress in the condenser. The increasing trend indicates possible air ingress, which requires the operation teams to perform a valve lineup around the condenser and observe for improvements. Suppose there are passing or leaking valves detected during the valve line. In that case, the maintenance teams can prepare for corrective maintenance in the upcoming outage, as air ingress negatively affects the condenser performance. If there is an increase in the cooling water pump motor currents, as seen in the case of CW Pump 1, where the current increases from 183.39 Amp to 190.95 Amp, there is a possibility of barnacles obstructing the CW intake into the condenser, which requires cleaning works in the condenser box to be carried out. The plant commissioning data manual obtains the target backpressure at CW inlet temperature and backpressure due to CW flow. The variation was due to CW flow increasing as the actual CW temperature rises increases. Although studies have been related to predictive condenser maintenance and methodologies (Jianlan et al., 2016; Matthews et al., 2020), no correlation exists between condenser performance and financial analysis. Overall, there is negative HR deviation for all three data sets causing daily losses of RM4,858, RM7,051, and RM8,968, respectively, at an ACP of RM24/GJ, and it is evident that the daily monetary losses increase as the ACP increases from RM 12/GJ to RM 24/GJ as illustrated in the last rows of Table 8.

Table 8
Condenser performance parameters

No.	Parameters		Unit	Data Set I	Data Set II	Data set III
1	Unit load		MWg	732.66	730.55	732.31
2	CW inlet temperature		°C	29.96	29.62	29.56
3	CW outlet temperature		°C	38.22	38.51	39.08
4	Actual CW temperature rise		°C	8.26	8.89	9.52
5	CW temperature rise at design conditions			7.46	7.44	7.45
6	Actual condenser TTD		°C	1.97	2.06	1.89
7	Optimum condenser TTD at design conditions			2.92	2.92	2.92
8	CEP discharge oxygen		%	4.47	4.50	4.48
9	CW pump 1 motor current		A	183.39	189.85	190.95
10	CW pump 2 motor current		A	179.50	179.13	179.06
11	LP1 exhaust pressure		mbar-A	86.22	85.74	88.08
12	LP2 exhaust pressure		mbar-A	79.43	81.65	84.84
13	Condenser vacuum		mbar-A	79.15	85.06	86.31
14	Condenser pressure		mbar-A	74.57	76.11	77.75
15	Target back pressure at CW inlet temperature		mbar-A	70.79	70.62	70.76
16	Back pressure due to CW flow		mbar-A	78.34	79.54	81.98
17	Variation due to CW flow			7.55	8.92	11.22
18	Variation due to air ingress /dirty tubes			-3.77	-3.43	-4.24
19	Total variation from the target			3.78	5.49	6.98
20	Daily gains/ losses (RM/day)	ACP:RM12/GJ	RM	-2,429	-3,525	-4,484
		ACP:RM18/GJ	RM	-3,644	-5,288	-6,726
		ACP:RM24/GJ	RM	-4,858	-7,051	-8,968

CONCLUSION

An analysis to evaluate the impact of various aspects influencing the HR of the CFPP by means of HR deviation has been carried out. The analysis incorporates financial analysis with the influence of ACP included in the study, which is of great benefit as not much importance has been given to the financial analysis of CFPP in previous studies. The HR deviation analysis utilizes real-life plant data, improving the accuracy of the results and outcome as commissioning and PGT data have also been considered. The results obtained in this study apply to other subcritical CFPPs provided the baseline figures for the CFPP are available. It was found that the most significant negative HR deviation is for the RAH flue gas exit temperature with a negative HR deviation of 137.9 kJ/kWh leading to an annual monetary loss of RM17.6 million at an ACP of RM24/GJ and the superheater contributes the least negative HR, and reheater spray flows with HR deviation of 2.63 kJ/kWh and 15.77 kJ/kWh, respectively causing annual monetary losses of RM0.34 million and RM2.02 million respectively at an ACP of RM24/GJ. This trend of gains or losses will also be similar for other CFPPs as the effect of deviation in key parameters will be the same such as monetary losses due to lower main steam temperature and so forth for the other parameters. The monitoring of HR deviation can also provide an indicator of underlying issues in the unit. The ranking of which parameters affecting HR the most are also highlighted so that operation and maintenance personnel can focus more on significant parameters.

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