Thermal Simulation of the TIAC System for Muara Karang CCPP Block 2: Feasibility Study for Power, Efficiency, and Emission Improvements

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Abstract. This study conducted a thermal simulation of the turbine inlet air cooling (TIAC) system for Muara Karang combine cycle power plant (CCPP) Block 2, focusing on its feasibility for enhancing power output, efficiency, and reducing greenhouse gas (GHG) emissions. Implementing TIAC on gas turbine generator) GTG 2.1 increased power output from 235 MW to 252.2 MW gross of power, reduced the heat rate, and improved plant efficiency. Financial analysis showed viability, with the internal rate of return (IRR) rising from 14.36% to 14.44%, surpassing PT. PLN's 9.28% threshold, and the net present value (NPV) increasing by Rp. 31.1 billion. GHG emission intensity decreased from 0.6018 kgCO2e/kWh to 0.6007 kgCO2e/kWh.

Keywords: *efficiency; greenhouse gas emissions; heat rate; output power; turbine inlet air cooling.*

1 Introduction

Indonesia has pledged to limit the global temperature rise to below 2°C, with efforts to achieve a 1.5°C target, as outlined in the Paris Agreement ratified by the President of Indonesia [1]. In the electricity sector, gas-fired power plants (GTPPs) and CCPPs remain crucial for grid stability amid increasing renewable energy adoption, offering lower GHG emissions[2],[3]. The sector is embracing environmentally friendly and high-efficiency technologies, with TIAC recognized by the authors as a potential enhancement for CCPP performance, as highlighted by Dabwan *et al.* [4]. Gas turbine performance fluctuates with ambient temperature, affecting air mass flow and heat rate, as noted by Komuro *et al.* [5], Nordin *et al.* [6], Erdem and Sevilgen [7]. Figure 1 issued by Mitsubishi Heavy Industries (MHI) in [8], shows the relationship between power output, air flow rate, and heat rate as functions of ambient temperature. Currently, a single gas turbine at CCPP Block 2 Muara Karang produces only 235 MW at 29°C, below the 250 MW commissioned condition. However, based on the correction factor graph in Figure 1, reducing inlet air temperature to 20°C could increase

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power output to 251.5 MW. This study explores the thermal simulation of the TIAC system for Muara Karang CCPP Block 2, focusing on GTG Unit 2.1, as part of an evaluation aimed at enhancing power generation, optimizing performance, and minimizing GHG emissions.

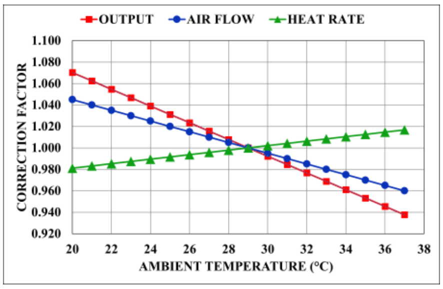

Figure 1 Correction factor of M701F3 gas turbine Muara Karang Block 2 [8]

Three key limitations are identified: (1) GTG 2.1 assumed to operate in open cycle mode, (2) operational parameters are based on peak load conditions, and (3) the impact of ambient temperature on the GTG auxiliary system is not considered. The study scope includes six activities: (1) selecting the cooling method for TIAC, (2) calculating the cooling load, (3) modeling and simulating the TIAC system using Aspen HYSYS, (4) conducting a financial feasibility analysis, (5) calculating GHG emissions intensity, and (6) designing the layout of TIAC equipment. The findings address five primary areas: (1) the thermal design of the TIAC system, (2) performance data of GTG 2.1 with and without TIAC, (3) GHG emissions intensity data, (4) layout recommendations for GTG 2.1 TIAC equipment, and (5) the results of the financial analysis.

2 Literature Review

2.1 TIAC studies in Indonesia

Studies on TIAC implementation in Indonesia have utilized various approaches to enhance the efficiency and performance of CCPP, as demonstrated by Subagio and Garchia [9], Zulfikry and Darmanto [10]. However, these studies assumed a constant specific heat capacity of air (c_p) and did not account for the bypass factor of the cooling coil, resulting in a relatively lower cooling load calculation. Building on these studies, further investigation into TIAC design for CCPP Block 2 at Muara Karang has become essential. This study focuses on validating cooling load calculations by accounting for changes in air enthalpy during the cooling and dehumidification process and the cooling coil bypass factor is included to ensure the TIAC cooling load in GTG 2.1 reflects actual operating conditions.

2.2 *Choosing the TIAC System for CCPP Block 2 Muara Karang*

According to weather data for North Jakarta in 2023 issued by BMKG [11] showed in Figure 2, the highest temperature was recorded on October 17, reaching 37.2°C with a humidity level of 72%. Under these environmental conditions, reaching a target temperature of 20°C cannot be accomplished through the evaporative cooling approach, as it is constrained by the wet-bulb temperature threshold [12].

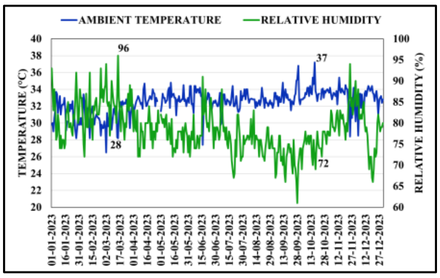

Figure 2 Environmental conditions in North Jakarta, 2023 [11]

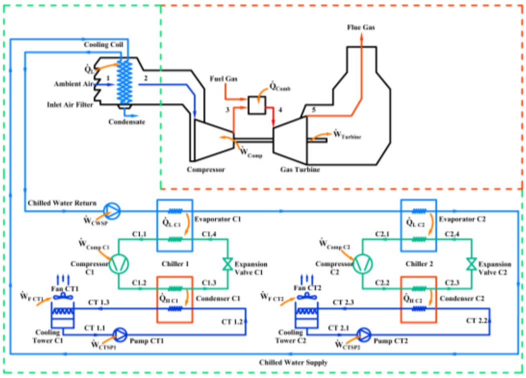

Figure 3 Proposed TIAC scheme for GTG 2.1 [5]

An alternative method that can achieve the cooling target is TIAC with mechanical compression chiller (MC), absorption chiller (AC), or thermal energy storage (TES). TES was not selected in this study due to limited space at CCPP Block 2 Muara Karang, as chillers and TES equipment require extensive area. Thus, the methods considered are TIAC MC or AC. In this study, the chosen method is TIAC MC, for several reasons. First, the use of TIAC MC minimizes the need for modifications at the CCPP, requiring only adjustments to the intake air filter (IAF). Second, the MC method is more economical than AC due to its lower initial investment cost and the absence of complex modifications to the heat recovery steam generator (HRSG). Third, AC incurs higher costs and is a more complex system, requiring larger space and a large cooling tower for waste heat rejection as discussed by Çengel *et al.* in [13]. Fourth, AC is more challenging to maintain, as it is less common than vapor-compression systems.

3 Methodology

3.1 CCPP Block 2 Muara Karang Existing Condition

The CCPP Block 2 Muara Karang is owned by PT. PLN Nusantara Power, a subsidiary of PT. PLN (Persero), is located northeast of Jakarta. It consists of two Mitsubishi model M701F3 gas turbine-generators, two HRSG, and three steam turbine-generators (STG) [8]. The plant operates in a 2 on 3 configuration in full-block mode or 1 on 2 in half-block mode, with an installed capacity of 710 MW, though the currently declared net capacity is only 680 MW [14]. Currently, GTG 2.1 produces only 235 MW, below its 250 MW commissioning output.

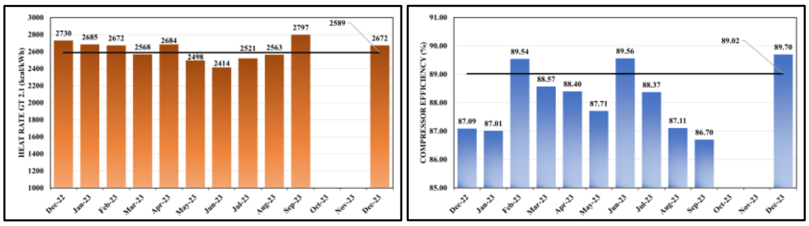

Figure 4 a) Heat Rate, and b) Efficiency GTG 2.1 in 2023 [14]

The heat rate of GTG 2.1 varies throughout the year, influenced by load adjustments made by the dispatcher to meet grid demand, as reported by the Muara Karang CCPP operation planner division [14]. Compressor efficiency degradation due to dirt accumulation can also contribute to heat rate increases. The 2023 heat rate performance test (high heating value basis) results, shown in Figure 4a, range from 2414 kcal/kWh to 2797 kcal/kWh. For comparison, the baseline heat rate in August 2012 was 2589 kcal/kWh when the unit produced 250 MW. Performance tests were not conducted in November and December 2023, as GTG 2.1 was not in operation. Figure 4b shows the 2023 compressor efficiency data, with values ranging from 86.7% to 89.7%, compared to the 2012 baseline of 89.02%. Higher efficiency values indicate that blade washing has been performed, whereas lower efficiency values suggest the presence of dirt accumulation on the blades. The average operating parameters from the December 2023 performance test and the October 2009 commissioning data are summarized in Table 1. These data, alongside existing conditions and commissioning report information, form the basis for the simulation model.

Table 1 Operating parameters of existing [14] and commissioning conditions [17].

Operating Parameters	Conditions	
	Existing	**Commissioning**
Power output (P)	237.8 MW	251.1 MW
Ambient temperature (T_a)	32.8 °C	30 °C
Ambient pressure (p_a)	101.34 kPa	100.69 kPa
Relative humidity (RH)	N/A	N/A
Compressor efficiency (η_c)	89.7%	N/A
Compressor discharge pressure (p_c)	1582.79 kPa	1569.06 kPa
Compressor discharge temperature (Tc)	453.23 °C	436.7 °C
Gas mass flow rate ($\dot{m}_g$)	4.916×10^4	4.895×10^4 kg/h
High heating value (HHV)	13264.84 kcal/kg	N/A
Gas temperature (T_g)	200 °C	199 °C
Gas pressure (p_g)	4026 kPa	3972 kPa
Exhaust temperature (T_e)	604.8 °C	604.9 °C

3.2 Cooling load calculation

The air conditioning in the IAF undergoes cooling and dehumidification, with not all air passing through the cooling coil coming into contact with its surface. Air that bypasses the cooling coil has a higher temperature than the air that makes contact. The fraction of air bypassing the cooling coil surface is defined as the bypass factor (BF).

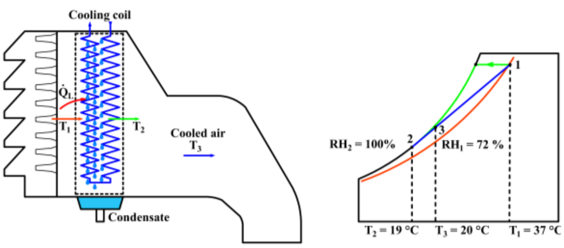

Figure 5 a) Cooling scheme in the IAF b) Cooling and dehumidification process with bypass factor line.

According to ARI standards referenced in the work of Stanford III and Spach [16], the BF for a cooling coil ranges from 0.049 to 0.08. In this study, a BF value of 0.05 was selected for cooling coil design and cooling load calculations. Using the method from [16], under extreme conditions with an inlet air temperature of T_1=37°C, the cooling coil surface temperature T_2 is calculated as 19°C to achieve the target turbine inlet air temperature of T_3=20°C. The cooling load was calculated following the method described in [13]. Based on the correction factor in Figure 1, the volumetric flow rate at 37°C is 0.96, resulting in an inlet flow rate of 508.8 m^3/s (≈509 m^3/s). Under conditions of T_1=37°C and RH=72%, with a cooling coil surface temperature of T_2=19°C, the cooling load for the TIAC system is calculated to be 31,321.97 kW (≈31,322 kW). The cooling scheme for

GTG 2.1 inlet air and its environmental conditions is shown in Figure 5a, while Figure 5b illustrates the cooling and dehumidification process on a psychrometric chart with the BF line.

3.3 Procedure for Simulating the Turbine Inlet Air Cooling Model

The thermal simulation modeling of the GTG 2.1 TIAC system in Aspen HYSYS consists of three stages. In the first stage, the GTG 2.1 model is configured to commissioning conditions, achieving a power output of 250 MW and reflecting the correlation between power output and ambient temperature from the manual data Figure 1. For verification, the model is tested to output 235 MW by adjusting compressor and turbine efficiencies to current data while keeping other input parameters constant. The second stage involves modeling the refrigeration system to determine chiller specifications that meet the TIAC cooling load requirements. The input parameters for the refrigeration system are set to achieve a chiller capacity that meets the cooling load requirements of the TIAC system. The AART-200s chiller [5] is selected as a reference, but due to unavailable catalog specifications, detailed modeling is conducted in Aspen HYSYS. In the third stage, the refrigeration system is integrated with the GTG 2.1 open-cycle model. The system includes components such as the chilled water supply system and cooling tower, resembling conventional chiller systems as shown in Figure 3.

3.4 GTG Simulation in Aspen HYSYS

The GTG 2.1 model in Aspen HYSYS is based on the gas turbine block flow diagram (BFD) by Liu *et al.* [17], using the Peng-Robinson fluid package. Liu's *et al.* CCPP model predicts parameter conditions under various dispatcher-specified loading scenarios. In this study, several modifications to Liu et al.'s model were made to meet the specific requirements. For instance, the inlet compressor valve and HRSG damper components were removed from the BFD. These components were excluded because, in this simulation, GTG 2.1 is assumed to operate in steady conditions at full load in open cycle mode. Therefore, the compressor and gas turbine maps, which represent performance under different loading conditions, were also not applied. A seal air bearing flow was added to the compressor outlet separator to better represent GTG 2.1's airflow distribution. Airflow data for combustion, stator cooling, seal air bearing, and rotor cooling were estimated and validated against GTG 2.1 data in Figure 1, as actual data is proprietary and reserved for the manufacturer under confidential long-term service agreements. Table 2 summarizes the operating parameters input into the simulation model, while Tables 3 and 4 detail the compositions of ambient air and natural gas fuel, respectively. Aspen HYSYS is a software focuses on chemical process modeling. To approximate actual GTG 2.1 conditions, the modeled power output is adjusted using the generator efficiency and power factor. The dry atmospheric air composition used, based on NOAA

US data [18], is shown in Table 3, with water vapor set at 0%. Adjustments were made to ensure the fractions sum to one, resulting in 0.7809, 0.2096, and 0.0095 for Nitrogen, Oxygen, and Argon, respectively.

Table 2 Simulation input parameters

Input Parameters	Value	Notes
Ambient temperature (T_a)	20 °C – 37 °C	Observed variable
Ambient pressure (p_a)	101.3 kPa	Constant
Relative humidity (RH)	72 %	Constant
Specific volume of air (v)	0.8802 m^3/kg	See psychrometric chart
Air volume flow rate ($\dot{V}_{air}$)	530 m^3/s	CF $\dot{V}_{air}$ = - 0.005 T_{air} + 1.145
Dry air mass flow rate ($\dot{m}_{air}$)	2.168 × 10^6 kg/h	$\dot{m}_{air} = (\dot{V}_{air} /v) \times 3600s$
Compressor efficiency (η_c)	90%	Constant
Compressor output pressure (p_c)	1569 kPa	Constant
Comb. air mass flow rate ($\dot{m}_{comb}$)	90% comp. air	Constant
Stator cool. air mass flow rate ($\dot{m}_{SC}$)	5% of comp. air	Constant
Rotor cool. air mass flow rate ($\dot{m}_{RC}$)	4.95% comp. air	Constant
Bearing seal air mass flow rate ($\dot{m}_{BS}$)	0.05% comp. air	Constant
Adiabatic turbine efficiency (η_t)	90%	Constant
Exhaust pressure (p_e)	101.3 kPa	Constant
Fuel gas mass flow rate ($\dot{m}_{gas}$)	4.902 × 10^4 kg/h	CF $\dot{m}_{gas}$ = - 0.0069 T_a + 1.2001
Gas temperature (T_{gas})	200 °C	Constant
Gas pressure (p_g)	4026 kPa	Constant
Generator power factor (PF)	0.9735	Constant
Generator efficiency (η_G)	0.9850	Constant

Table 3 Atmosphere air composition [18]

Water Vapor	Nitrogen	Oxygen	Argon
0%	0.7808	0.2095	0.0093
1%	0.7730	0.2070	0.9200
2%	0.7652	0.2053	0.9100
3%	0.7574	0.2032	0.9000

Table 4 Fuel gas composition [14]

Components	Fraction
Methane	0.9461
Ethane	0.0261
Nitrogen	0.0018
Propane	0.0052
i-Butane	0.0011
n-Butane	0.0014
i-Pentane	0.0003

Fuel gas composition was sourced from the December 2023 performance test report [14], prepared by the planning and operation control division of CCPP Block 2 Muara Karang. Figure 6 illustrates the Aspen HYSYS simulation results for open cycle GTG 2.1 operation.

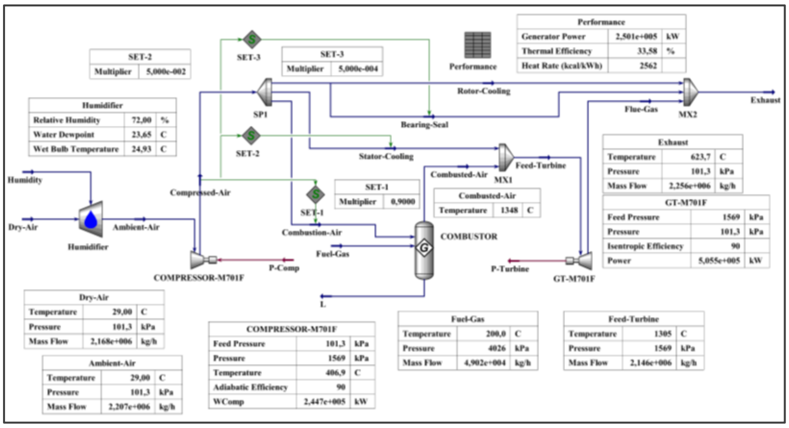

Figure 6 Open cycle mode GTG 2.1 simulation model

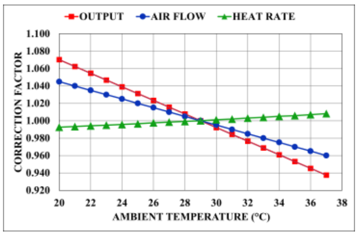

Figure 7 GTG 2.1 model's correction factor

The GTG 2.1 simulation model outputs an exhaust temperature of 623.7°C, exceeding the acceptable range of 600°C–615°C. This discrepancy arises from using a Gibbs reactor to model the combustor, which assumes complete combustion, leading to higher exhaust temperatures [19]. Figure 7 illustrates the correction factor from the simulation results. In the simulation model the output CF shows a relatively similar trend derived from the manual book. However, there is a difference in the slope of the simulated heat rate CF, where the trend is more gradual compared to that presented in the manual book.

3.5 Refrigeration system simulation in Aspen HYSYS

The chiller for the GTG 2.1 TIAC system must handle a cooling load of 31,322 kW or 8,906 RT. However, currently available chillers on the market have a maximum capacity of < 6,000 RT [20]**.** To achieve the required chiller capacity, an alternative is to arrange lower-capacity chillers in series. The refrigeration system modeled utilizes R-134a as the refrigerant and applies several specification data identical to those in the AART-200s chiller [5][20]. Table 5 presents the input parameters for the refrigeration system model with a capacity of 15,661 kW.

Table 5 Refrigeration cycle parameters

Parameters	Value
Cooling load (Q_L)	15,661 kW
Subcooled temperature (T_{C1})	10 °C
Compressor suction pressure (p_{C1})	320 kPa
Refrigerant mass flow rate ($\dot{m}_{R\text{-}134a}$)	372,492 kg/h
Compressor discharge pressure (p_{C2})	899 kPa
Compressor adiabatic efficiency (η_{comp})	97 %
Expansion valve discharge pressure (p_{C4})	320 kPa
Evaporator outlet temperature (T_{C5})	10 °C

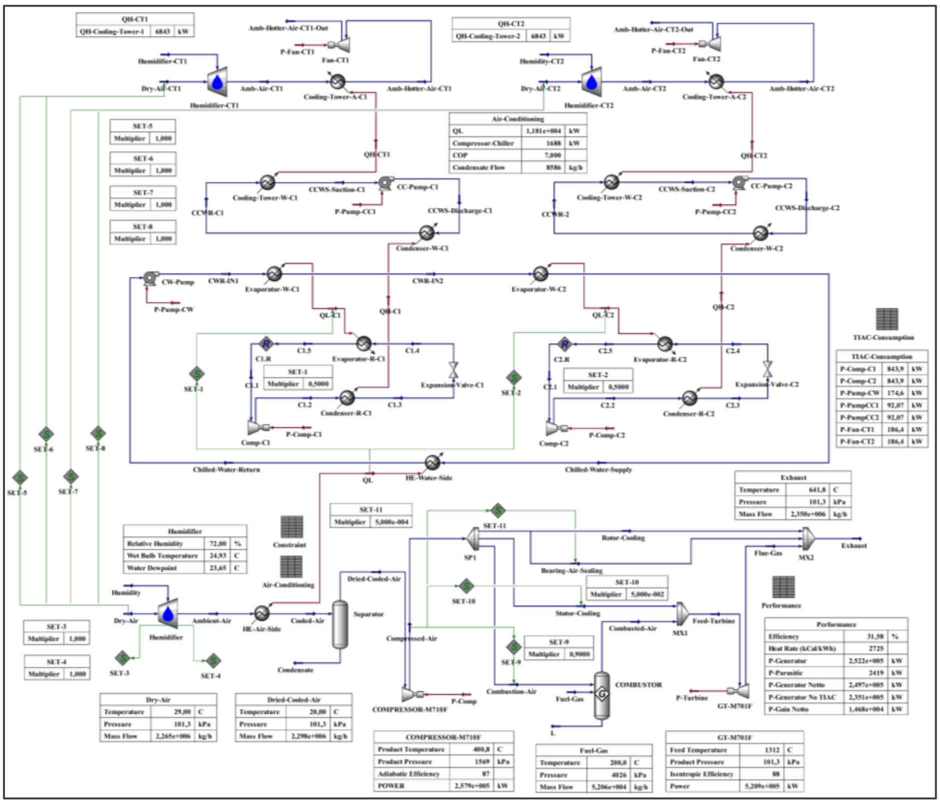

Figure 8 GTG 2.1 TIAC system model

3.6 GTG 2.1 TIAC System Model

The modeled GTG 2.1 TIAC system uses the same assumptions and input parameters as the simulation model for GTG 2.1, along with the previously developed refrigeration system. Figure 8 presents the Aspen HYSYS simulation model for GTG 2.1. The cooling system in this model is equipped with a chilled water supply system and a cooling tower, similar to conventional chillers. At an ambient air temperature of 29°C and a relative humidity of 72%, and with degraded compressor efficiency, GTG 2.1 equipped with a TIAC system can generate 252.2 MW gross of power. Simulation data under various environmental conditions are further explained in the results and discussion section.

4 Results and Discussion

4.1 Comparison of GTG 2.1 Performance with and without TIAC

The TIAC system for GTG 2.1 is simulated under various conditions representing the environment in Muara Karang. The design parameters for ambient temperature and relative humidity for GTG 2.1 in Muara Karang are 29°C and 72%, respectively [8]. The allowable minimum and maximum relative humidity ranges are 44% and 97%, respectively[8].

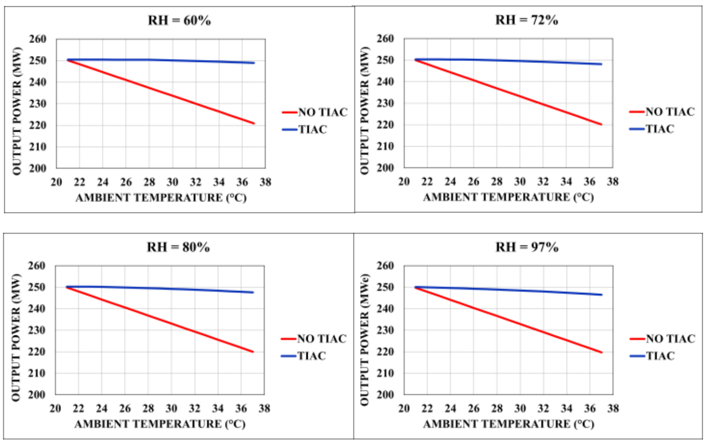

Figure 9 Output power with and without TIAC system

The minimum allowable humidity is 44%, yet the location generally experiences higher levels. Simulations were performed at relative humidities of 60%, 72%, 80%, and 97%, with ambient temperatures ranging from 21°C to 37°C. Figure 9 demonstrates that gas turbine net output declines as ambient temperature increases, aligning with research that attributes performance reductions to lower air density at higher temperatures in [5], [21]. In all scenarios, turbine net output without TIAC is consistently lower than with TIAC, highlighting the system's ability to maintain or improve performance. At 29°C, the net power gain with TIAC is 14.8 MW, 14.7 MW, 14.4 MW, and 13.9 MW at RH levels of 60%, 72%, 80%, and 97%, respectively. Similarly, at 37°C, the power increases are 28 MW, 27.9 MW, 27.6 MW, and 26.8 MW for the corresponding RH levels.

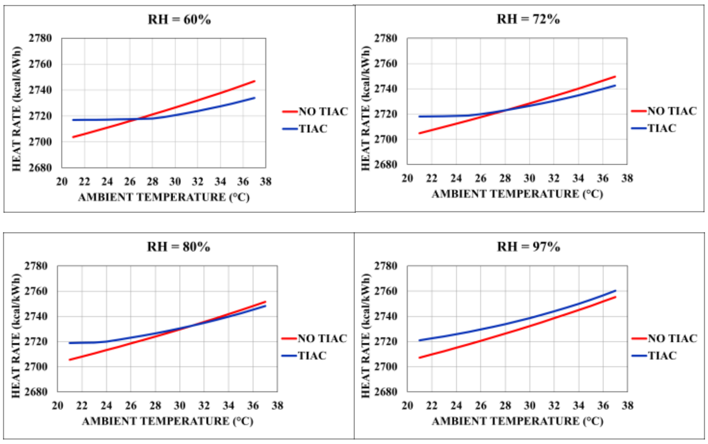

Figure 10 Heat rate with and without TIAC system

The TIAC system demonstrates significant benefits at higher ambient temperatures and lower RH levels, although its effectiveness diminishes slightly under very high humidity. Nonetheless, it consistently outperforms non-TIAC conditions by maintaining higher power output levels as temperatures rise. As shown in Figure 10, the gas turbine heat rate increases with ambient temperature, consistent with studies indicating higher fuel consumption per unit of electricity at elevated temperatures [6],[9]. At RH levels of 60%, 72%, and 80%, the heat rate with TIAC exceeds that without TIAC below ambient temperatures of 26.5°C, 28°C, and 30.5°C, respectively.

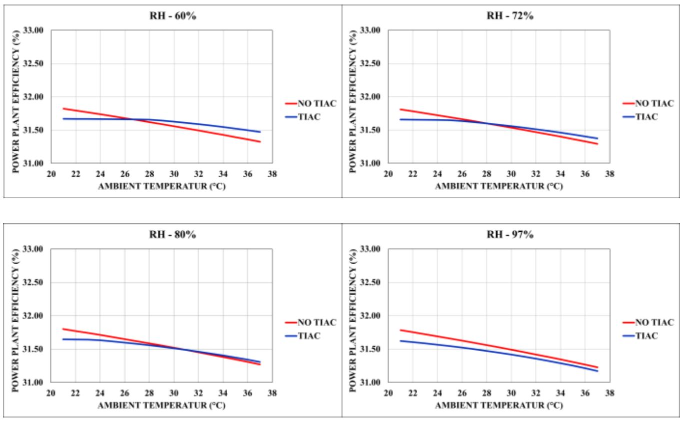

Figure 11 Power plant efficiency with and without TIAC system

Thus, optimal operation of the TIAC system is recommended at temperatures above these thresholds to ensure efficiency gains. Conversely, at 97% RH, typically corresponding to rainy conditions, the heat rate with TIAC is consistently higher across all simulated temperatures compared to non-TIAC conditions. Under such high RH scenarios, TIAC usage should be minimized or avoided, as the energy required for operation outweighs the efficiency benefits. The data presented in Figure 10, further supported by Figure 11, demonstrate an increase in efficiency for GTG 2.1 equipped with the TIAC system at ambient temperatures above 26.5°C, 28°C, and 30.5°C, corresponding to relative humidity (RH) levels of 60%, 72%, 80%, and 97%, respectively.

4.2 Greenhouse gas emission calculation

The calculation of GHG emissions is based on the guidelines issued by Indonesian Directorate General of Electricity [24]. In this study, the GHG emissions calculation follows the tier 1 methodology. Table 6 presents a comparison of GHG emissions produced by GTG 2.1 with and without the use of TIAC in a year. The capacity factor of GTG 2.1 in a year is assumed as 95%. The output power of the simulated GTG 2.1 is evaluated under ambient air conditions of 34°C and 72% relative humidity. Under these conditions the output power of the non-TIAC and TIAC systems are 225,800 kW and 248,817 kW, respectively.

Table 6 Greenhouse gas emission comparison with or without TIAC in a year

Output Power (kW)	Production (kWh)	Fuel Gas Consumption (MMBTU)	Total Emission (kgCO2e)	Emission Intensity (kgCO2e/kWh)
225,800	1,879,107,600	19,105,644.150	1,130,777,102	0.6018
248,817	2,070,655,074	21,014,997.560	1,243,783,138	0.6007

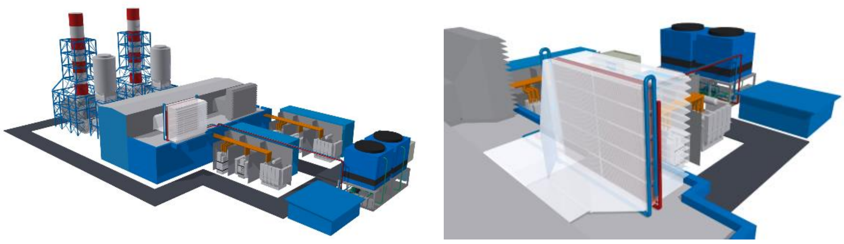

Figure 12 GTG 2.1 with TIAC system layout

4.3 TIAC GTG 2.1 equipment layout

Figure 12 illustrates the layout of GTG 2.1 at CCPP Block 2 Muara Karang with the TIAC system installed. The dimensions of IAF for GTG 2.1 increase due to the addition of the cooling coil component, necessitating modifications to the IAF and its supporting floor structure. However, based on the existing layout of

PLTGU Block 2 Muara Karang, there remains adequate space to accommodate the installation of the TIAC equipment for GTG 2.1.

4.4 Financial analysis

The investment cost for TIAC installation is challenging to obtain from contractors without serious commitment from the project owner. One vendor lists a TIAC investment cost of approximately $200 up to $400 per kW of capacity increase [25]. In this study, the installation cost is assumed to be $400 per additional kW. With a targeted power increase of 15 MW, the total investment cost is estimated at $6 million, while the annual maintenance cost is assumed to be $130,000. Financial analysis, conducted using PLN's financial feasibility assessment for Muara Karang CCPP Block 2, assumes the TIAC system installation on GTG 2.1 during its 2027 major inspection. By 2028, the net power capacity is projected to rise from 680 MW to 695 MW, with maintenance costs continuing through 2050. The project achieves a 14.44% IRR, up from 14.36% without TIAC, surpassing PT. PLN's 9.28% threshold. The NPV increases by Rp 31.1 billion, confirming profitability.

5 Conclusion

The thermal simulation model of the TIAC system for GTG 2.1 successfully increased power output from 235 MW to 252.2 MW gross of power. The implementation of the TIAC system also reduced the heat rate and GHG emissions intensity while enhancing overall plant efficiency. Moreover, the layout of the TIAC equipment is compatible with the available space within the CCPP Block 2 Muara Karang area. Financial analysis indicates that the project is feasible. Future work could involve collaboration with a TIAC contractor to conduct a more detailed risk assessment and financial evaluation.

6 Acknowledgement

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