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THERMODYNAMIC ANALYSIS OF HYDROGEN-ASSISTED COMBUSTION ON THE PERFORMANCE AND EMISSIONS OF A GAS TURBINE POWER PLAN

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ABSTRAK

Meningkatnya permintaan energi global, khususnya pada sektor kelistrikan, berkontribusi terhadap peningkatan emisi Gas Rumah Kaca (GRK), terutama dari pembangkit berbahan bakar fosil. Salah satu upaya dekarbonisasi adalah penerapan hydrogen-assisted combustion pada Pembangkit Listrik Tenaga Gas (PLTG). Penelitian ini menganalisis pengaruh penambahan hidrogen terhadap kinerja dan emisi turbin gas 2000E v94.2 menggunakan pendekatan termodinamika dengan perangkat lunak DWSIM. Variasi fraksi mol hidrogen yang digunakan adalah 10, 20, dan 30% terhadap bahan bakar gas alam. Hasil simulasi menunjukkan bahwa peningkatan fraksi hidrogen meningkatkan daya keluaran turbin masing-masing sebesar 2,2, 5, dan 8%, serta meningkatkan efisiensi pembangkit sebesar 0,5, 1, dan 2%. Emisi CO_2 berkurang sebesar 1,3, 3, dan 5%. Hasil ini menunjukkan potensi hydrogen-assisted combustion untuk meningkatkan kinerja sekaligus menurunkan emisi PLTG. Namun, implementasinya memerlukan kajian lebih lanjut terkait pencampuran bahan bakar, pembentukan NOx, batasan material, dan keselamatan.

***Kata kunci**: co-firing, dekarbonisasi, emisi, hidrogen, turbin gas*

ABSTRACT

The increasing global demand for energy, particularly in the electricity sector, contributes to rising greenhouse gas (GHG) emissions, especially from fossil fuel-based power generation. One decarbonization strategy is the utilization of hydrogen-assisted combustion in gas turbine power plants. This study analyzes the effects of hydrogen addition on the performance and emissions of a 2000E v94.2 gas turbine using a thermodynamic approach with the software DWSIM. Hydrogen mole fractions of 10, 20, and 30% were blended with natural gas. The simulation results show that increasing the hydrogen fraction increases turbine power output by 2.2, 5, and 8%, respectively, while improving plant efficiency by 0.5, 1, and 2%. CO_2 emissions decrease by 1.3, 3, and 5%, respectively. These results demonstrate the potential of hydrogen-assisted combustion to improve gas turbine performance while reducing carbon emissions. However, further studies are required regarding fuel mixing, NOx formation, material limitations, and safety.

***Keywords**: co-firing, decarbonization, emission, gas turbine, hydrogen*

1. INTRODUCTION

Electricity demand in Indonesia continues to increase in line with population growth, industrial development, urbanization, and expanding economic activities. Indonesia's electricity consumption reached 1337 kWh per capita in 2023, representing an increase of 13.98% compared with 1173 kWh per capita in 2022. In the long term, national electricity demand is projected to reach 1885 TWh by 2060, with per-capita electricity consumption exceeding 5000 kWh. This trend indicates that a reliable electricity supply will remain a strategic requirement for supporting national development. However, increasing electricity generation, which remains highly dependent on fossil fuels, may also intensify greenhouse gas emissions. Therefore, the development of the electricity generation sector must be directed toward more efficient and lower-carbon technologies (Ministry of Energy and Mineral Resources, 2021 & 2024).

The increase in greenhouse gas emissions has become one of the primary causes of global warming and climate change. Through the Paris Agreement, countries worldwide committed to limiting the increase in global average temperature to well below 2°C above pre-industrial levels while pursuing efforts to limit the temperature rise to 1.5°C. To maintain the possibility of achieving the 1,5°C target, global greenhouse gas emissions must be reduced by approximately 43% by 2030. Indonesia has strengthened its commitment through the 2022 *Enhanced Nationally Determined Contribution* (ENDC), which targets an emission reduction of 31.89%, equivalent to approximately 912 million tonnes of CO_2-equivalent, through domestic efforts and 43.20%, equivalent to approximately 1240 million tonnes of CO_2-equivalent, with international support by 2030. In the energy sector, the emission reduction targets are 358 million tonnes of CO_2-equivalent through domestic efforts and 446 million tonnes of CO_2-equivalent with international support. These targets provide an important basis for developing decarbonization technologies in Indonesia's electricity generation sector (ENDC Republic of Indonesia, 2022).

Gas turbine power plants play an important role in electricity systems because of their operational flexibility, relatively short start-up time, and ability to respond rapidly to changes in system demand. These characteristics make gas turbines particularly relevant for supporting the integration of intermittent renewable energy sources, since fluctuating wind and solar generation requires flexible conventional power plants that can respond quickly to maintain grid reliability (Liese et al., 2019). Although natural gas combustion produces lower carbon dioxide emissions than coal or petroleum products for the same amount of energy produced, it remains a hydrocarbon fuel and still generates CO_2 during combustion (EIA, 2024). Therefore, strategies are required to enable existing gas turbine assets to remain operational while reducing their emission intensity. One promising approach is hydrogen-assisted combustion or hydrogen co-firing, in which a portion of the natural gas supplied to a gas turbine is replaced with hydrogen. Previous studies have shown that hydrogen co-firing in gas turbine power plants can reduce CO_2 emissions and improve several performance indicators, making it a potential transitional technology between fossil-fuel-based power generation and low-carbon energy systems. (Nugraha et al., 2025)

Hydrogen has a high energy content per unit mass and contains no carbon atoms; therefore, its combustion does not directly produce CO_2 at the point of use. Adding hydrogen to natural gas reduces the carbon content of the fuel mixture and can subsequently decrease the rate of CO_2 emissions generated during combustion. However, the life-cycle emissions of hydrogen remain highly dependent on the production pathway and the energy source used, since hydrogen produced from unabated natural gas or coal can still have significant upstream CO_2-equivalent emissions, whereas electrolytic hydrogen depends strongly on the carbon intensity of the electricity supply (IEA, 2024). The application of hydrogen in gas turbines also introduces several technical challenges because hydrogen has a higher flame temperature and a much higher flame speed than natural gas, which may increase metal temperatures, thermal stress, thermal-acoustic effects, flashback risk, and NO_x formation. In addition, hydrogen-fueled gas turbines must address operability issues such as combustion dynamics, increased emissions, and material compatibility, particularly when retrofitting existing gas turbine systems originally designed for natural gas operation (Zhou et al., 2024). Consequently, hydrogen utilization in gas turbines must be evaluated not only in terms of CO_2 reduction, but also with respect to operating limits, combustion stability, turbine inlet temperature, material compatibility, NO_x control, and the capabilities of the existing fuel and burner systems. (NETL, 2022).

Several studies have demonstrated the potential of hydrogen as a blended fuel for gas turbines. Nugraha et al. (2025) simulated hydrogen addition ranging from 5-30% by volume in a Mitsubishi M701F gas turbine using Aspen HYSYS under 100, 75, and 50% load conditions. The results indicated that increasing the hydrogen fraction improved thermal efficiency while reducing both the CO_2 emission rate and emission intensity. At a hydrogen fraction of 30%, the CO_2 emission rate decreased by approximately 12.94%, while the maximum increase in thermal efficiency ranged from 1.94 to 2.23%, depending on the operating load. These results demonstrate that the effects of hydrogen are influenced not only by fuel composition but also by gas turbine loading conditions.

A more integrated assessment was conducted by Fauzi et al. (2026) through a numerical simulation of hydrogen and natural gas combustion in an F-class gas turbine combustor. The study reported that hydrogen addition reduced CO_2 emissions by up to 36% but simultaneously increased NO_x emissions by up to 41% because of the higher combustion reactivity and temperature. From an economic perspective, hydrogen utilization increased fuel costs to approximately 1.65 times those of natural-gas operation, while the implementation of a carbon-credit mechanism reduced the cost ratio to approximately 1.50. These findings demonstrate a trade-off among carbon-emission reduction, increased NO_x formation, changes in thermal operating parameters, and higher fuel costs. Therefore, the implementation of hydrogen co-firing requires a technical and economic assessment that considers the specific characteristics of the power-generation unit and its actual operating conditions.

Despite the growing number of studies on hydrogen co-firing, investigations specifically addressing its application to the gas turbine 2000E V94.2 using actual operating data from an Indonesian power plant remain limited. Furthermore, several previous studies have evaluated only a limited number of loading conditions or have focused primarily on thermal efficiency and CO_2 emissions without integrating changes in operational parameters, cycle-performance indicators, thermal risks, and fuel economics. An assessment of gas turbine at the Power Plant is therefore required because the unit operates in an open-cycle configuration over a wide range of loads. Evaluations at 143, 120, 100, 80, 60, and 35 MW can provide a more representative description of the influence of hydrogen under baseload, part-load, and minimum-load conditions. The selected hydrogen mole fractions enable the identification of performance trends and potential operational limitations within the existing thermodynamic model. However, practical implementation would require further assessment of burner compatibility and fuel-system modifications. Previous studies have generally evaluated a limited number of operating loads or focused primarily on thermal efficiency and CO_2 emissions without simultaneously considering broader cycle-performance indicators and thermal operating parameters (Hassan & Manji, 2023; Nugraha et al., 2025; Fauzi et al., 2026). The novelty of this study lies in the application of DWSIM to a 2000E V94.2 gas turbine using actual operating data from an Indonesian power plant across six operating loads and three hydrogen mole fractions, while simultaneously evaluating net power output, turbine inlet temperature (TIT), cycle efficiency, back work ratio (BWR), specific fuel consumption (SFC), net plant heat rate (NPHR), and CO_2 emissions.

Accordingly, this study aims to investigate the effects of hydrogen-assisted combustion on the performance and emissions of the gas turbine 2000E V94.2. Thermodynamic modelling was performed using the open-source DWSIM software under steady-state conditions and assuming complete combustion (Hassan & Manji, 2023; Oliveira de Medeiros, 2025). The baseline natural-gas model is validated against performance-test data at a load of 143 MW and verified using actual operating data at loads ranging from 120 to 35 MW. The analysis covers changes in turbine inlet temperature, net power output, exhaust gas temperature, thermal efficiency, back work ratio, specific fuel consumption, net plant heat rate, and CO_2 emissions. The results are expected to provide a technical basis for hydrogen implementation in existing gas turbines, support PLN's power-sector decarbonization strategy, and contribute to achieving Indonesia's net-zero-emission target by 2060 (Ministry of Energy and Mineral Resources, 2023)

2. MATERIALS AND METHODS

2.1 Research Framework

This study investigates hydrogen-assisted combustion in a 143 MW 2000E V94.2 gas turbine (Table 1), using the open-source DWSIM software (Figure 1). Three hydrogen mole fractions of 10%, 20%, and 30% were evaluated at six operating load conditions: 143, 120, 100, 80, 60, and 35 MW. The analysis focuses on the effects of hydrogen addition on gas turbine thermodynamic performance and CO_2 emissions. This scenario-based analysis (Figure 2) was conducted to identify the effects of hydrogen addition under baseload, part-load, and minimum-load operating conditions.

Table 1. Specification Gas Turbine 2000E v94.2 (Source : Siemens, SGT5-2000E performance data and plant performance test record, internal document)

Parameters	Unit	Simple Cycle
Fuel	-	Gas
Low heat value LHV	kJ/kg	48,160
Nominal output at Gen terminals	MW	146.8
Nominal eff. at Gen terminals	%	33.33
Exhaust gas flow	kg/s	494.4
Exhaust GT temperature	^oC	558
Fuel Consumption	kg/s	9.1
IGV	%	100%
Reference conditions :		
Speed	rpm	3,000
Ambient Temp	^oC	30
Barometric Pressure	hPa	1,013
Relative Humidity	%	82.9
Press loss at compressor inlet	hPa	10
Press loss at turbine outlet	hPa	10
Nominal Power Factor	-	0.8
Nominal excitation power losses ca.	MW	0.1

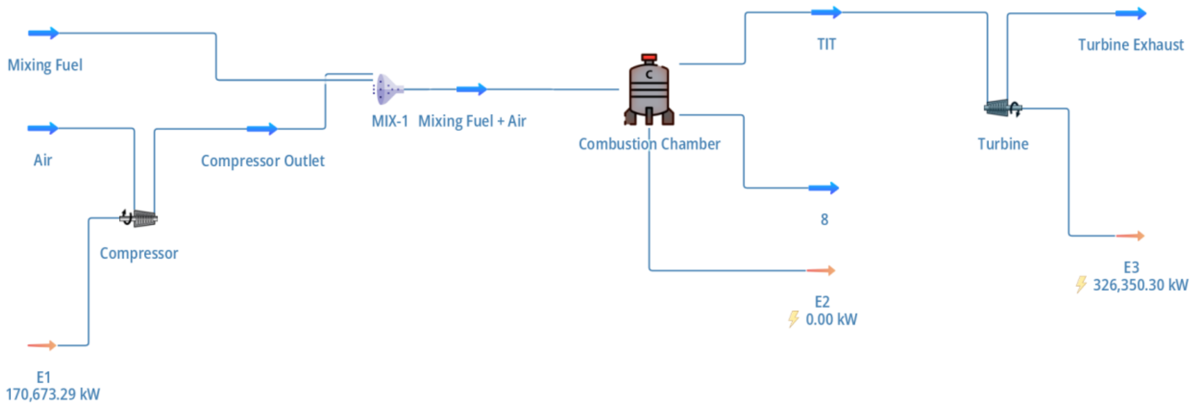

Figure 1. Gas Turbine Model Developed in DWSIM (Source : Authors' model developed in DWSIM)

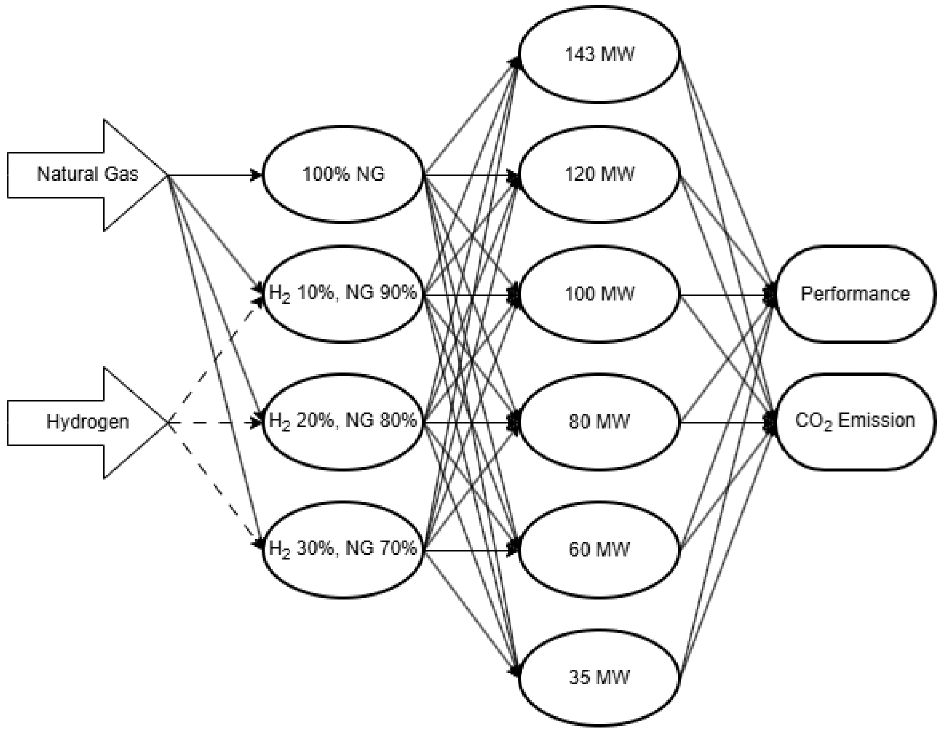

Figure 2. Hydrogen-Assisted Combustion Simulation Scenario

This study assumes complete combustion with these equations for natural gas combustion :

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (1)$$

$$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O \quad (2)$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \quad (3)$$

$$C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O \quad (4)$$

$$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O \quad (5)$$

$$C_6H_{14} + \frac{19}{2}O_2 \rightarrow 6CO_2 + 7H_2O \quad (6)$$

and this equation for hydrogen combustion :

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (7)$$

Thus, the overall combustion reaction for hydrogen-assisted combustion can be expressed as follows :

$$(1-\mathrm{n})\mathrm{C}_x\mathrm{H}_y + n\,\mathrm{H}_2 + \left((1-n)\left(x+\frac{y}{4}\right)+\frac{n}{2}\right)\mathrm{O}_2 \rightarrow (1-\mathrm{n})x\,\mathrm{CO}_2 + \left((1-n)\,\frac{y}{2}+n\right)\mathrm{H}_2\mathrm{O} \ldots\ldots (8)$$

where *n* represents the mole fraction of hydrogen. This parameter defines the proportion of hydrogen co-fired with methane (Table 2), and is used to evaluate the influence of hydrogen addition on the combustion characteristics, thermodynamic performance, and CO_2 emissions of the gas turbine system.

Table 2. Fuel Gas Composition Used in Simulation (Source : Fuel-gas laboratory analysis using GPA 2261:2020 and GPA 2172:2019)

Composition (%mol)	Result	Method
Methane	97.37	GPA 2261:2020
Ethane	2.0806	
Propane	0.2495	
i-Butane	0.0918	
n-Butane	0.1236	
i-Pentane	0.0269	
n-Pentane	0.0106	
Nitrogen	0.047	
Carbon Dioxide	0	
C6	0	
Gross Heat Value (BTU/ft^3)	1,037.2484	GPA 2172:2019
Nett Heat Value (BTU/ft^3)	934.7852	
Compressibility Factor	0.9979	
Specific Gravity	0.5714	

2.2 Simulation Assumptions and Boundary Conditions

The gas turbine model was developed in DWSIM under steady-state operating conditions using the Peng–Robinson equation of state as the thermodynamic property package. The combustion chamber was represented using a conversion reactor, in which complete combustion reactions were specified for the hydrocarbon components of natural gas and hydrogen. Heat losses from the compressor, combustion chamber, connecting streams, and turbine were neglected. The isentropic efficiencies of the compressor and turbine were set to 85.81% and 87%, respectively.

The air and fuel mass-flow rates were specified based on direct field observations at each operating load. The measured boundary conditions used in the simulation are presented in Table 3. At operating loads of 143, 120, 100, 80, 60, and 35 MW, the total fuel mass-flow rates were 9.10, 7.60, 6.43, 5.32, 3.95, and 2.18 kg/s, respectively. The corresponding air mass-flow rates were 485, 443, 375, 317, 237, and 170 kg/s. The air–fuel ratio was not imposed as an independent simulation parameter but was determined from the measured air and fuel mass-flow rates for each load condition.

Table 3. Boundary Conditions

Operating Load (MW)	Total Fuel Mass Flow (kg/s)	Air Mass Flow (kg/s)
143	9.1	485
120	7.6	443
100	6.43	375
80	5.32	317
60	3.95	237
35	2.18	170

For the hydrogen-assisted combustion cases, the total mass-flow rate of the natural-gas–hydrogen fuel mixture was maintained at the same value as the baseline natural-gas mass-flow rate for each operating load. Hydrogen was introduced by modifying the fuel-stream composition to hydrogen mole fractions of 10%, 20%, and 30%, while the remaining mole fraction consisted of natural gas. Therefore, the effects observed in the simulation represent the consequences of changing the fuel composition while maintaining the total fuel mass-flow rate at each load condition.

The detailed pressure, temperature, and pressure-drop data were obtained from plant operating records and are not presented in full because of operational data restrictions. No independent turbine inlet temperature controller was applied. Consequently, the turbine inlet temperature was calculated as a simulation output from the fuel composition, air and fuel flow rates, inlet conditions, combustion reactions, and energy balance of the conversion reactor. The simulation was considered converged when all material streams and unit operations were successfully calculated and no numerical convergence errors were displayed by DWSIM.

2.3 Hydrogen-Assisted Combustion Parameter

Hydrogen co-firing ratios were defined on a molar basis at hydrogen mole fractions of 10%, 20%, and 30%. For gaseous mixtures at the same temperature and pressure, the mole fraction is equivalent to the volumetric fraction. However, because the total fuel flow rate in the DWSIM model was specified on a mass basis (kg/s), the lower heating value of the blended fuel used for the energy analysis was also expressed on a mass basis. Therefore, the hydrogen mole fraction was converted into a mass fraction according to:

$$W_{H2} = (x_{H2} M_{H2}) / [x_{H2} M_{H2} + (1 - x_{H2})\, M_{NG}] \quad (9)$$

where x_{H2} is the hydrogen mole fraction, M_{H2} is the molecular weight of hydrogen, and M_{NG} is the average molecular weight of natural gas. The natural-gas mass fraction is subsequently obtained as $W_{NG} = 1 - W_{H2}$. The mass-based lower heating value of the blended fuel is then determined as:

$$LHV_{mix} = (W_{NG} \times LHV_{NG}) + (W_{H2} \times LHV_{H2}) \quad (10)$$

Accordingly, the thermal energy supplied by the fuel can be expressed as:

$$Q_{fuel} = \dot{m}_{fuel} \times LHV_{mix} \quad (11)$$

where $\dot{m}_{fuel}$ is the total natural-gas–hydrogen mixture mass-flow rate. This formulation ensures consistency between the mass-flow basis used as the simulation boundary condition and the heating-value basis employed in the energy analysis. The volumetric heating value reported from the fuel-gas analysis is retained only as a fuel-property reference and is not directly multiplied by the mass-flow rate. The mass-based LHV formulation was used to characterize the thermal energy content of the blended fuel. The combustor heat input used in the cycle-efficiency calculation was obtained directly from the DWSIM energy balance based on the enthalpy difference across the combustion chamber, as described in Section 2.4.

2.4 Thermodynamic Analysis

The gas turbine operates based on the Brayton cycle, which consists of four thermodynamic processes: isentropic compression in the compressor, isobaric heat addition in the combustion chamber, isentropic expansion in the turbine, and isobaric heat rejection through the exhaust gases to the atmosphere. A thermodynamic analysis was performed to evaluate the performance and efficiency of each major component, including the compressor, combustion chamber, and turbine :

The compressor work : $\frac{\dot{W}c}{\dot{m}} = h_2 - h_1$..(12)

The heat input in combustion chamber $\frac{\dot{Q}in}{\dot{m}} = h_3 - h_2$..(13)

The turbine work : $\frac{\dot{W}t}{\dot{m}} = h_3 - h_4$...(14)

Therefore, the overall system efficiency can be expressed as follows:

$Cycle_{eff} = \eta = \frac{\dot{W}t/\dot{m} - \dot{W}c/\dot{m}}{\dot{Q}in/\dot{m}} = \frac{(h3-h4)-(h2-h1)}{h3-h2}$..(15)

2.5 Emissions Analysis

The CO_2 emission analysis was conducted based on the combustion reactions presented in Equations (1) – (7). The simulation generated flue gas data, from which CO_2 emissions were evaluated using two different indicators: the CO_2 emission rate and the CO_2 emission intensity. The CO_2 emission rate represents the total mass of carbon dioxide emitted from the combustion process per unit time and is expressed in (kg CO_2/h). In contrast, the CO_2 emission intensity represents the amount of carbon dioxide emitted per unit of electrical energy generated and is expressed in (kg CO_2/kWh). These two indicators provide complementary measures for assessing the environmental performance of the gas turbine under different hydrogen co-firing conditions.

3. RESULTS AND DISCUSSION

3.1 Model Validation

Model validation was performed to ensure that the simulation accurately represented the actual operating conditions and that any discrepancies between the simulated and measured data remained within an acceptable and justifiable range. The validation was conducted by comparing the simulation results with performance test data obtained directly under base-load operating conditions with temperature control active, representing the plant's optimal operating state in which all major components are expected to operate at their highest efficiency. The validation results, including the error margins for the compressor outlet temperature, net power output, and exhaust temperature, are presented in Figure 3. The close agreement between the simulated and measured values demonstrates that the developed model can reliably predict the thermodynamic performance of the gas turbine. Furthermore, these results indicate that the specified conversion reactions, mass balances, and energy balances were successfully solved within an acceptable error margin, confirming the validity of the simulation model for subsequent performance and emission analyses.

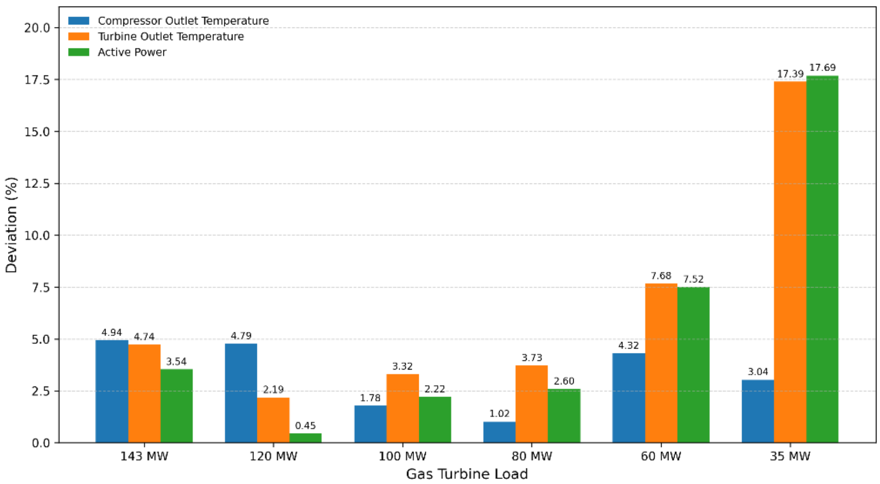

Figure 3. Model Validation at Different Operating Loads

The 143 MW baseline model was validated against performance-test data, whereas the models at 120, 100, 80, 60, and 35 MW were verified against actual operating records. At loads between 80 MW and 143 MW, the principal validation parameters generally showed deviations below approximately 5%. Larger deviations were observed at 60 MW and 35 MW, indicating reduced model accuracy under low load operating conditions and under off-design conditions.

3.2 Hydrogen-Assisted Combustion Simulation Results

Hydrogen co-firing was implemented by introducing hydrogen mole fractions of 10, 20, and 30% into the fuel mixture under different operating loads of 143, 120, 100, 80, 60, and 35 MW. The simulation was performed to evaluate the effects of hydrogen addition on the thermodynamic performance and environmental characteristics of the gas turbine. Key thermodynamic parameters, including back work ratio, turbine work, and cycle efficiency, as well as CO_2 emissions, were determined from the material stream data generated by the simulation process. The corresponding simulation results are presented in Figure 4.

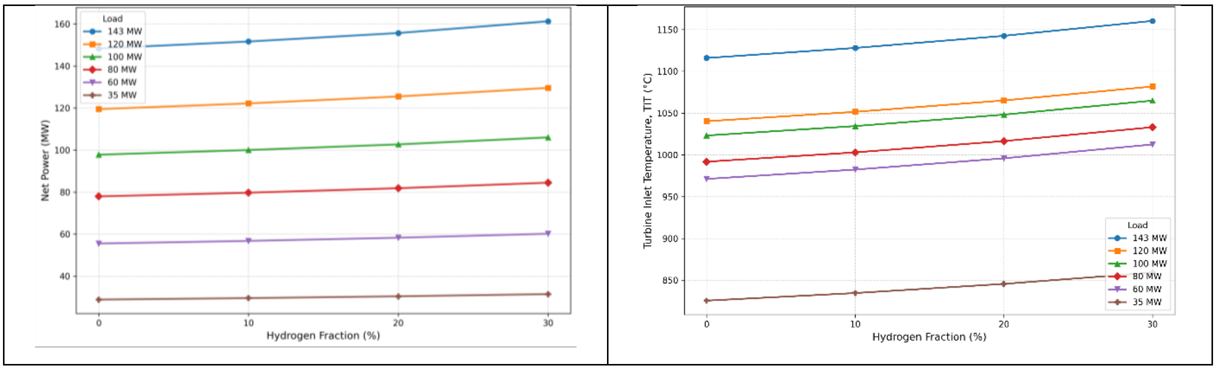

Figure 4. Effect of Hydrogen Mole Fraction on Net Power Output and TIT at Different Operating Loads

Hydrogen addition consistently increased the net power output across all operating loads. However, the simultaneous increase in turbine inlet temperature indicates that the performance improvement is accompanied by higher thermal loading, which must be considered with respect to burner and material operating limits (Figure 5).

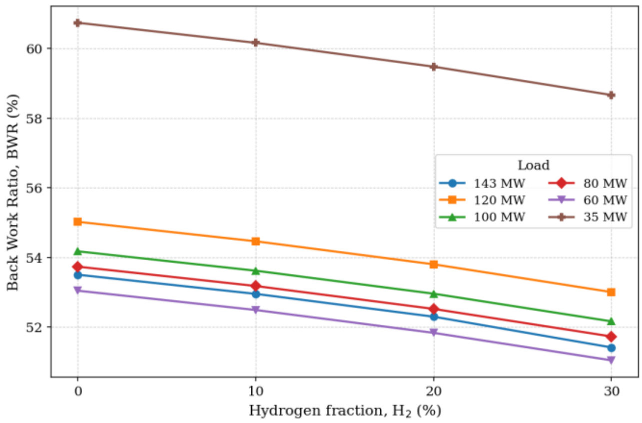

Figure 5. Effect of Hydrogen Mole Fraction on Back Work Ratio at Different Operating Loads

The thermodynamic performance indicators show that hydrogen-assisted combustion improves the gas turbine cycle performance, as indicated by the decreasing trends of Back Work Ratio (BWR), Specific Fuel Consumption (SFC), and Net Plant Heat Rate (NPHR). At 143 MW, the BWR decreased from 53.50% under natural-gas operation to 51.41% at 30%

H_2. A similar trend was observed at lower loads, where the BWR decreased from 60.74 to 58.66% at 35 MW, although the BWR remained higher at low-load operation due to the greater relative influence of compressor work on turbine output. The lowest BWR was obtained at 60 MW with 30% H_2, reaching approximately 51.04%, followed by 51.41% at 143 MW. This indicates that hydrogen addition improves the internal work distribution of the Brayton cycle by increasing turbine work while compressor work remains relatively stable.

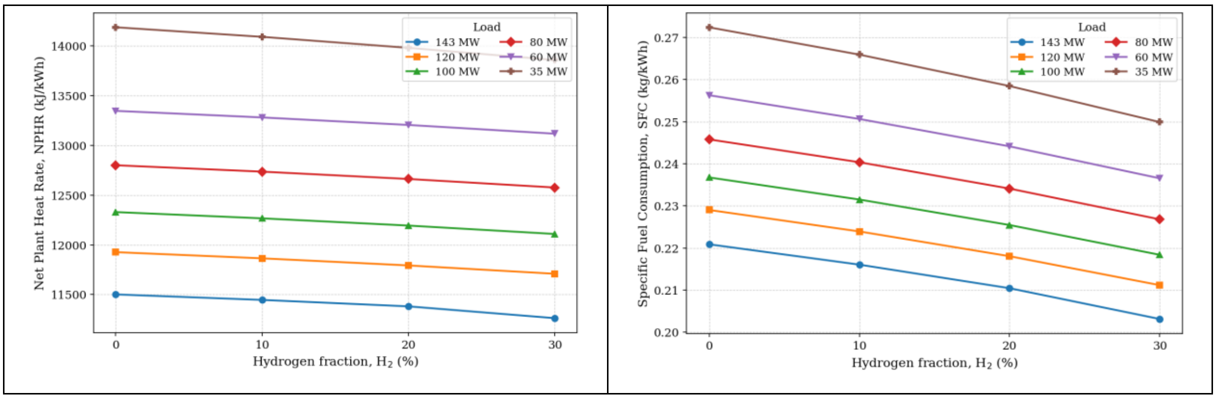

Figure 6. Effect of Hydrogen Mole Fraction on NPHR and SFC at Different Operating Loads

The SFC decreased consistently with increasing hydrogen fraction because the same imposed total fuel mass-flow rate produced a higher net power output. Consequently, the amount of fuel mass associated with each unit of generated electrical energy decreased. At 143 MW, the SFC decreased from 0.22086 kg/kWh at 0% H_2 to 0.20312 kg/kWh at 30% H_2, corresponding to a reduction of 0.01774 kg/kWh or approximately 8.03%. At 120 MW, the SFC decreased from 0.22902 to 0.21116 kg/kWh, while at 100 MW it decreased from 0.23675 to 0.21837 kg/kWh. The same behavior was observed at lower loads, where the SFC decreased from 0.24578 to 0.22679 kg/kWh at 80 MW, from 0.25628 to 0.23654 kg/kWh at 60 MW, and from 0.27240 to 0.24990 kg/kWh at 35 MW. These results show that hydrogen-assisted combustion improves fuel utilization across all load conditions, with the highest absolute SFC occurring at the lowest load due to part-load operation.

The NPHR also decreased as the hydrogen fraction increased, indicating improved heat-to-power conversion. At 143 MW, the NPHR decreased from 11,501.68 kJ/kWh at 0% H_2 to 11,262.94 kJ/kWh at 30% H_2, representing a reduction of 238.74 kJ/kWh or approximately 2.08%. At 120 MW and 100 MW, the NPHR decreased from 11,926.54 to 11,708.97 kJ/kWh and from 12,328.89 to 12,108.73 kJ/kWh, respectively. At lower loads, the NPHR decreased from 12,799.50 to 12,575.56 kJ/kWh at 80 MW, from 13,345.88 to 13,116.41 kJ/kWh at 60 MW, and from 14,185.78 to 13,856.80 kJ/kWh at 35 MW. Although hydrogen addition reduced NPHR at all loads, the absolute NPHR remained higher at low-load conditions because gas turbines operate less efficiently under part-load/off-design conditions. Overall, the reductions in BWR, SFC, and NPHR confirm that hydrogen-assisted combustion enhances thermodynamic performance by increasing useful turbine output, improving fuel utilization, and reducing the heat input required per unit of net electrical power.

3.3 Effect of Hydrogen-Assisted Combustion on Thermodynamics

The cycle efficiency increased gradually with the addition of hydrogen at all operating loads. Cycle efficiency is defined as the ratio between net power output and heat input to the combustor, where a higher value indicates better conversion of fuel thermal energy into useful power. In this study, the increase in cycle efficiency was mainly caused by the increase in turbine work and net power output after hydrogen enrichment, while the compressor work remained relatively stable. At the 143 MW load condition, the cycle efficiency increased from 31.30% under natural-gas operation to 31.96 at 30% H_2, corresponding to an improvement of 0.66 percentage points or approximately 2.12%. The same trend was observed at 120 MW, where the efficiency increased from 30.19 to 30.75%, and at 100 MW, where it increased from 29.20 to 29.73%. At lower loads, the efficiency also improved, increasing from 28.13 to 28.63% at 80 MW, from 26.98 to 27.45% at 60 MW, and from 25.38 to 25.98% at 35 MW. These results confirm that hydrogen-assisted combustion improves the thermodynamic performance of the Brayton cycle across all load variations. However, the absolute efficiency remained lower at part-load operation, particularly at 60 MW and 35 MW, because compressor work and other internal losses represented a larger portion of the turbine output. Therefore, the highest cycle efficiency was obtained at high-load operation, while the lowest efficiency occurred at minimum-load operation.

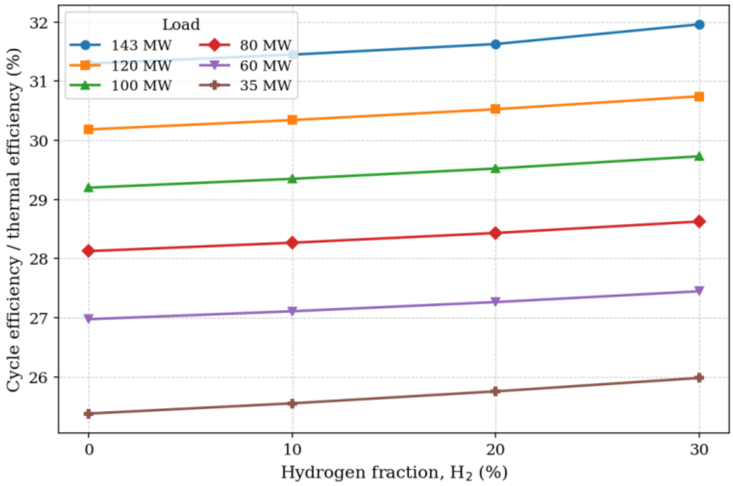

Figure 7. Effect of Hydrogen Mole Fraction on Cycle Efficiency at Different Operating Loads

3.4 Effect of Hydrogen-Assisted Combustion on CO_2 Emissions

Based on the simulation data, adding hydrogen consistently reduces CO_2 emissions across all load variations. This reduction occurs because hydrogen contains no carbon; therefore, replacing part of the natural gas with hydrogen decreases the carbon content of the fuel mixture and consequently reduces CO_2 formation during combustion. Increasing the hydrogen mole fraction to 10, 20, and 30% reduced CO_2 emissions by approximately 1.3, 3, and 5%, respectively. Under natural gas operation, the CO_2 emission rate ranged from 21.60 to 90.15 tonnes/h for loads between 35 and 143 MW. At a hydrogen mole fraction of 30%, the emission rate decreased to 20.52 – 85.67 tonnes/h. The highest absolute CO_2 reduction was obtained at a load of 143 MW, reaching 4.48 tonnes/h, while the reduction at the minimum load of 35 MW was 1.07 tonnes/h. At a 143 MW load, the specific CO_2 emissions dropped by 12.6% from 0.6078 to 0.5312 kg CO_2/kWh, and at a 35 MW load, the specific CO_2 emissions dropped by 12.82% from 0.7496 to 0.6535 kg CO_2/kWh.

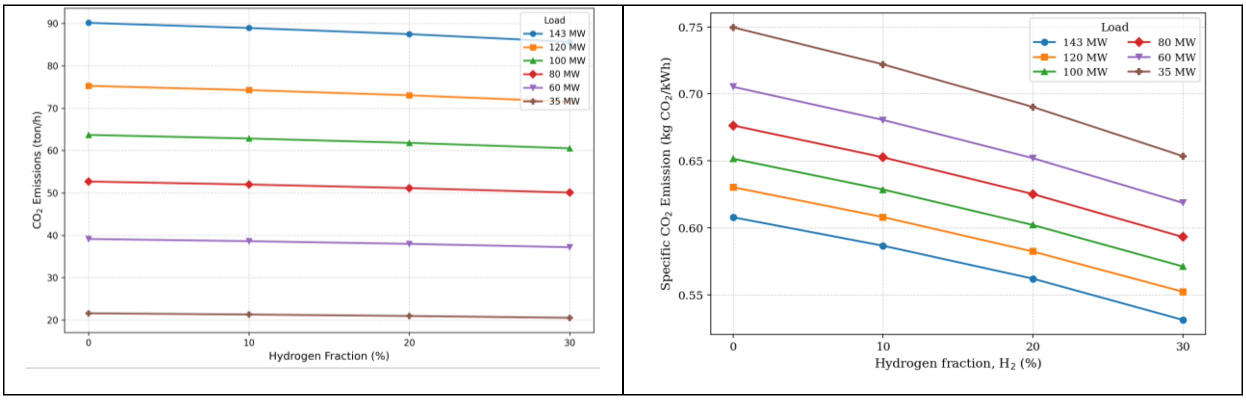

Figure 8. Effect of Hydrogen Mole Fraction on CO_2 Emissions at Different Operating Loads

4. CONCLUSIONS

The DWSIM-based thermodynamic simulation demonstrated that hydrogen-assisted combustion can increase the net power output and reduce the CO_2 emissions of the 2000E V94.2 gas turbine under operating loads of 143, 120, 100, 80, 60, and 35 MW. Hydrogen mole fractions of 10, 20, and 30% increased the net power output by approximately 2.2, 5, and 8%, respectively, while reducing CO_2 emissions by approximately 1.3, 3, and 5%. The greatest improvement was obtained at a hydrogen mole fraction of 30%, indicating that hydrogen co-firing has thermodynamic potential as a transitional decarbonization strategy for existing gas turbine power plants. However, these results represent simulation-based trends and should not be interpreted as confirmation of immediate technical feasibility at the actual power plant.

This study was conducted under steady-state conditions and assumed complete combustion. The detailed mechanisms of NO_x formation were not modelled, while flame stability, thermoacoustic behaviour, pre-ignition, and flashback risks were not evaluated. Burner compatibility with hydrogen-enriched fuel was also not experimentally verified, and a comprehensive economic analysis covering hydrogen production and supply costs, infrastructure modifications, safety systems, maintenance requirements, and carbon-credit benefits was not performed. Therefore, further research should include detailed combustion and NO_x modelling, computational fluid dynamics and experimental validation, burner and material compatibility assessments, and a comprehensive techno-economic evaluation before hydrogen co-firing is implemented commercially.

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