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PERFORMANCE AND EMISSION ANALYSIS OF HYDROGEN AND NATURAL GAS COFIRING IN COMBINED CYCLE GAS TURBINE POWER GENERATION

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The use of clean, abundant, and sustainable energy sources, such as solar and wind energy, is a strategy to reduce the reliance on fossil fuels and the danger of exposure to potentially harmful pollutants. However, increases in renewable energy utilisation might burden a power infrastructure due to its intermittent and variable characteristics. The intermittency of such renewables can be supported by a gas turbine power plant, especially if the gas turbines are fuelled with fuel that does not produce carbon emission. Using thermodynamic modelling software, this paper explains the technology and evaluates the performance of an existing natural gas fuelled CCGT plant in North Sumatera, Indonesia, if the facility is cofired with hydrogen. Hydrogen has a greater reactivity in comparison to natural gas, and related technological issues with hydrogen include faster flame speed, a higher adiabatic flame temperature, shorter autoignition delay periods, a broader flammability range, and increased volumetric fuel flow rate. Thermodynamic modelling demonstrates that plant production increases with the addition of H2 to the cofiring mixture, but CO2 emissions decrease.

Keywords: combined cycle, hydrogen, cofiring, gas turbine, thermodynamic simulation

1 INTRODUCTION

Numerous new projects have evolved to address the climate change caused by carbon dioxide (CO_2) emitted by the world's energy and transportation systems. The process through which the power industry reduces carbon emissions is known as the energy transition. This trend is characterized by the rapid deployment of renewable energy sources and the rapid decline of carbon-intensive coal usage [1]. Using energy sources that are clean, abundant and sustainable is one way to reduce dependence on fossil fuels and lower the risk of exposure to potentially hazardous emissions. However, because of the intermittent and inconsistent nature of their properties, efficient storage strategies are required. The lack of dispatchability is an issue with large increases in renewable power generation; Without the addition of storage or stabilizing capacity, increases in renewables can burden a power grid. This gap can be filled by gas turbines, but their long-term viability within a carbon-free energy ecosystem is questionable [2]. Renewable energies are capable of being stored as either chemical or electrical energy [3]. As a result of its advantageous qualities as an energy carrier, hydrogen is gaining increasing attention. To ensure sustainable development and environmental challenges, renewable energy sources must be used to generate hydrogen [4]. A benefit of gas turbines (GT) is their ability to operate on hydrogen (H_2), which does not produce carbon emissions when burnt. This includes both new and existing gas turbines that can be adapted to operate on high H_2 fuel [5]. In addition to CO_2, numerous energy systems also produce a variety of air pollutants, which cause environmental and respiratory health problems. The main source of NOx in most gas-fired systems is the ambient air itself, as its main ingredients (nitrogen, N_2 and oxygen, O_2) react at high temperatures. Several studies show the use of hydrogen (H_2) as a green energy carrier that can be carried through pipelines and consumed by a range of fixed and mobile sources, including power plants, heaters, and trucks. As a carbon-free fuel, hydrogen has the desirable attribute of not emitting CO_2 when burnt. However, H_2 combustion produces NOx because, as stated previously, NOx is produced when the air is heated to high temperatures [6] [7].

It is possible to utilize hydrogen in the combustion of GTs as a result of the various advantages related to its usage in combustion processes, especially those associated with environmental safety. Various factors, such as ambient condition such as operating temperature and humidity, equipment, and system configuration would impact the performance of hydrogen-powered GTs in the same way as they affect the performance of conventional fuel-powered GTs [8]. The use of H_2 as a GT fuel has been the subject of several investigations. When hydrogen is used in the combustion process, it may be necessary to change the system to prevent a loss in turbine performance [9]. These adjustments may require adjustment of the mass flow rate, pressure ratio, or design and structure of the cycle so that the GT combustor can burn a range of fuels containing hydrogen. In the research conducted by Yoshimura [10], hydrogen was combined with natural gas under lean premixing conditions using a centerline pilot injector. They observed that adding hydrogen can extend the stability limit and reduce NOx emissions.

Hydrogen has the ability to alter the properties of the flame and the combustion process when coupled with conventional fuels [11]. Various parameters, such as stability and shape transition, can influence the characteristics of the flame in combustors that use hydrogen-containing fuels [12]. Medina et al. researched the combination of hydrogen and ammonia combustion and showed a vigorous swirling flow may be used to generate a steady flame.

This finding was made feasible by combustion of the combination. In the presence of hydrogen as a fuel, new ways to boost the regularity of the combustion process have been investigated and tried [13].

In another study done by Therkelsen et al., using three sets of fuel injectors, they assessed the condition of a GT engine operating on hydrogen and natural gas. The injectors utilized variable amounts of premixing. Refinery of the mixture and reduction of the equivalence ratio were shown to minimize NO emissions; however, NO emissions were higher when hydrogen was used as the fuel, mostly due to the larger equivalence ratio [14]. Gazzani et al. observed that using nitrogen as fuel diluent in the case of a diffusive flame was more efficient than using water at the same stoichiometric flame temperature [15]. In the study done by Lee et al. of the GT combustion process, they observed that an increase in the amount of hydrogen in fuel could increase NOx emissions, which was correlated as an effect of increased heat input. An increased concentration of hydrogen improves the equivalence ratio, resulting in a higher flame temperature; therefore, NOx emissions increase [16]. Carbon dioxide emissions are minimized when pure hydrogen is used as fuel for GT engines; however, nitrogen oxide emissions can increase. The significantly faster flame speed of hydrogen and the shorter delay time might increase the possibility of increased NOx emissions and cause material damage due to flashback [17].

Despite the environmental advantages of using hydrogen in GT, this fuel is considerably more expensive than traditional fuels such as natural gas [18]. Hydrogen GTs are compatible with different forms of energy production. A novel GT architecture composed of biofuel, solar cells, an electrolyzer, and a post-firing hydrogen chamber was studied by Cen et al. Its performance was compared to that of a biomass-based combined cycle without hydrogen post-firing. In addition to improving capacity, the adoption of a post-firing hydrogen system reduces carbon dioxide emissions by 22.7% under ideal circumstances [19].

Several characteristics, such as plant load, ambient air temperature, ambient air pressure, ambient relative humidity, cooling water temperature, frequency, power factor and generator voltage, process energy extraction, fuel type and quality [20] and fuel pressure [19], typically influence off-design performance of gas turbines. Most GT manufacturers, including Siemens [22], [23], General Electric [2], [21], and Mitsubishi Heavy Industries [22] - [24], focus primarily on the development of engines that can burn hydrogen fuel as efficiently and as securely as possible. To assess the advantages and disadvantages of using unconventional fuels, it is necessary to examine the thermodynamic and environmental performance of power plants. This study reviews the current development of hydrogen cofiring in CCGT and analyses the performance of existing natural gas fueled CCGTs if cofired with hydrogen for the CCGT unit located in north Sumatera, Indonesia with a capacity of 400 MWe. For comparison, the performance of a heavy duty CCGT power plant operating on natural gas is studied. Then, using four cofiring configurations, the performance of the reference plant is re-evaluated, and a comparison of the four configurations at design conditions efficiency, power capacity, and primary energy consumption is presented.

2 MATERIALS AND METHOD

The study was divided into two sections. The objective of the first section was to identify the challenges of using H_2 fuels mixed with natural gas in the current gas turbine and combined cycle technologies to determine the limiting processes and components from the existing literature. The second section involves the evaluation of the plant performance of a commercial gas turbine if operated using a mixture of natural gas and H_2 fuel.

The power plant used in this study is a combined cycle gas turbine power plant (CCGT) with a capacity of 400 MWe located in North Sumatera, Indonesia. The plant uses 2 Gas Turbine (GT) – 2 vertical Heat Recovery Steam Generator (HRSG) – 1 Steam Turbine (ST) configuration as shown in Fig 1. GTs are industrial type V.94.2 with a rated capacity of 130 MWe and the ST are rated 150 MWe. The air composition used in the model is nitrogen (N_2) 75.30%, Oxygen (O_2) 20.20%, CO_2 0.02%, water (H_2O) 3,55% and Argon (Ar) 0,90%. The mass flow of the inlet air is 466.07 kg/s and the fuel flow is 8,83 kg/s.

Table 1. Input for plant model

Parameter	Unit	Value
Ambient Temperature	^oC	30
Ambient Pressure	bar	1.013
Relative Humidity	%	85
Altitude	m	3
Line Frequency	Hz	60
Cooling Water		Sea water
Cooling Water Temperature	^oC	30
Cooling Water Temperature rise (ΔT)		10

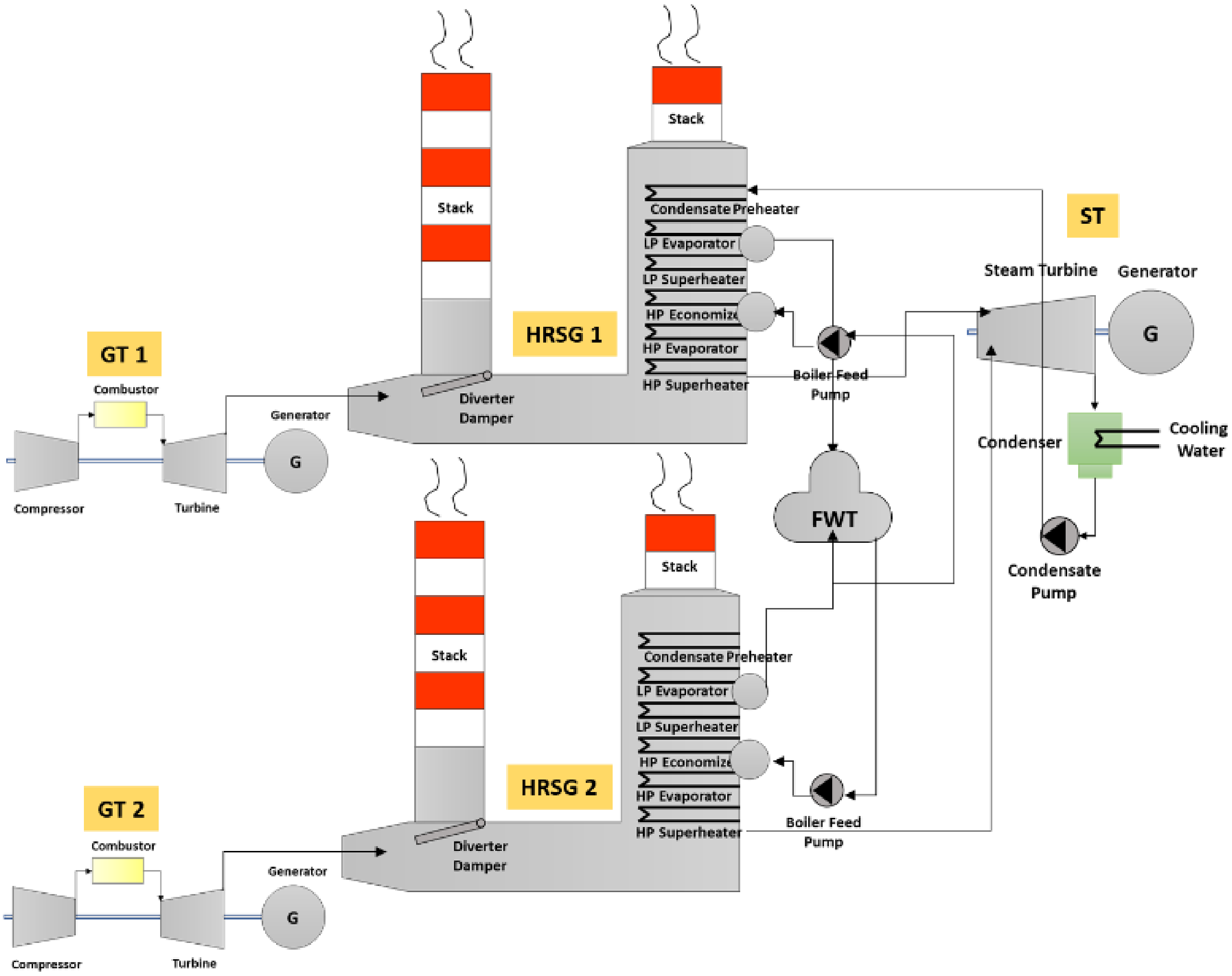

Fig 1.Simplified layout of the studied CCGT power plant

The plants are then modeled in Thermoflow GTPro thermodynamic simulation software, with the input parameters being obtained from the design specification of the CCGT plant and shown in Table 1. After that, GT Pro calculates the mass and heat balance, as well as the performance of the system [28].

Table 2. CCGT Plant Operating Design Specification

Gas Turbine	Unit	
Model		Type V94.2
Exhaust gas flow	kg s^{-1}	474.4
Pressure Ratio		9.97
Turbine Inlet Temperature (TIT)	^{o}C	1135
Turbine Exhaust temperature (Exh)	^{o}C	561.1
Gross electrical power output	MW	127.18
Gross efficiency	%LHV	30.88
Steam Turbine		
Steam pressures HP/LP	Bar	82.4/7.2
Seam temperature	^{o}C	525
Steam flow	kg s^{-1}	64.13
Condenser pressure	millibar	86
Gross electrical power output	MW	157.4
Combined Cycle Block		
Gross/Nett electrical power output	MW	411.4/402.8
Net Heat Rate	kJ kwh^{-1} LHV	7,353
Net efficiency	%LHV	48.96

Table 3. Natural Gas Composition

Parameter	Unit/Compound	Value
Composition (%v)	Methane	95.2471
	Ethane	3.6165
	Propane	0.7037
	i-Butane	0.1073
	N-Butane	0.1693
	i-pentane	0.0362
	N-pentane	0.0105
	Nitrogen	0.1015
LHV	kj kg^{-1}	35,131

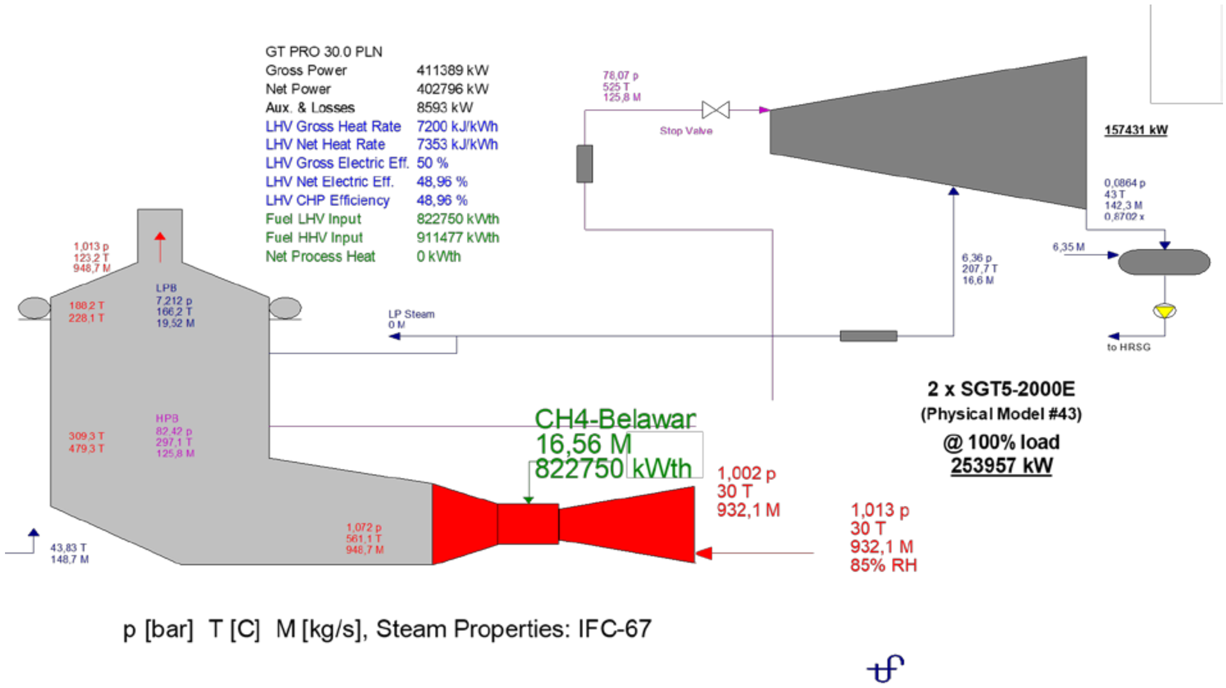

Fig 2.Mass balance of the studied CCGT power plant

Table 2 and Fig 2 show the operating conditions of the plant as well as the primary performance indicators from GT Pro calculation. When natural gas with the composition stated in Table 3 is used, this level of performance can be achieved. Then the fuel of the model is varied with four ratios of H_2 combustion, which is a volume mix of 5%, 10%, 20% and 30% with natural gas. The properties of the H_2 gas used in the simulation are industrial grade purity with a LHV of 119 MJ/kg. In the simulation the turbine gas inlet temperature is kept stable at 1135 ^oC. The items investigated that are used to evaluate the performance and emission of the CCGT in this study are shown in Table 4.

Table 4. Evaluation items

Evaluation	Investigated Items
Performance	Gross Output
	Efficiency
	Auxiliary Power
	Losses
	Heat Rate
Environmental	CO_2

3 RESULT AND DISCUSSION

3.1 Technology review

Existing gas turbine assets should be considered in the evaluation of a power-to-hydrogen system, as they can be converted to operate on hydrogen-based fuels. A feature of gas turbines is their adaptability to new fuels, such as those with a greater hydrogen component. Changing to a fuel with a greater hydrogen concentration may require adjustments to the gas turbine, gas turbine accessories, or the rest of the facility. The necessary adjustments are proportional to the hydrogen content of the fuel. If the new fuel is a mixture of hydrogen and natural gas, it may be necessary to make small adjustments to the controls and install new fuel nozzles [2]. Siemens has tested its burner technologies on an air combustion test apparatus with optical access to the flame zone. Four different hydrogen-enriched natural gas flames were investigated: 0%, 30%, 60% and 80% hydrogen. The results of flame imaging indicate that the addition of hydrogen significantly altered the size and form of the flame. The flame becomes shorter and more concentrated as the hydrogen concentration increases. For the 60% and 80% hydrogen flames, the flame has moved upstream, as has the core recirculation zone that anchors the flame. Dynamic pressure measurements in the wall of the combustion chamber confirm that a small amount of hydrogen in natural gas modifies the amplitude of dynamic pressure fluctuations and initially dampens the axial mode [29]. As a result of the strong reactivity of hydrogen, the key issue for premixed low NOx systems is the potential for flashback in the burner. Compared to natural gas, the technological problems associated with hydrogen include a higher flame speed, a higher adiabatic flame temperature, shorter delay times, a wider range of flammability, and an increase in the volumetric fuel flow rate [30] [31]. A test on a SGT-400 industrial gas turbine burner to study hydrogen-enriched combustion at atmospheric conditions shows that hydrogen volumetric composition of up to 30% could still maintain stable operation [32] and testing on the high pressure condition shows that up to 20% H_2 volumetric composition the combustion system can operate up to 20% of the H_2 volumetric composition without the risk of flashback [33].

3.2 Performance evaluations

The properties of natural gas and the gas mix are shown in Table 5. The Wobbe index of cofired fuel is still in the range of gaseous fuel for gas turbine operation [31]. With the increasing volume mix of H_2, the LHV and molar weight of the mixture are increasing as well, but the volumetric LHV are decreasing, this is due to the low volumetric energy density of H_2 compared to natural gas.

Table 5. Properties of the gas mixture

Mixed Gas Properties				
H2 %	LHV @ 25 ^{o}C	Volumetric LHV	M	Wobbe Index
	kj/kg	kJ/m^3	kg/kmol	MJ/m^3
0	49,679	34,335	16.91	50.62
5	50,116	33,113	16.16	49.98
10	50,595	31,891	15.42	49.33
20	51,706	29,446	13.93	48.04
30	53,083	27,002	12.44	46.74

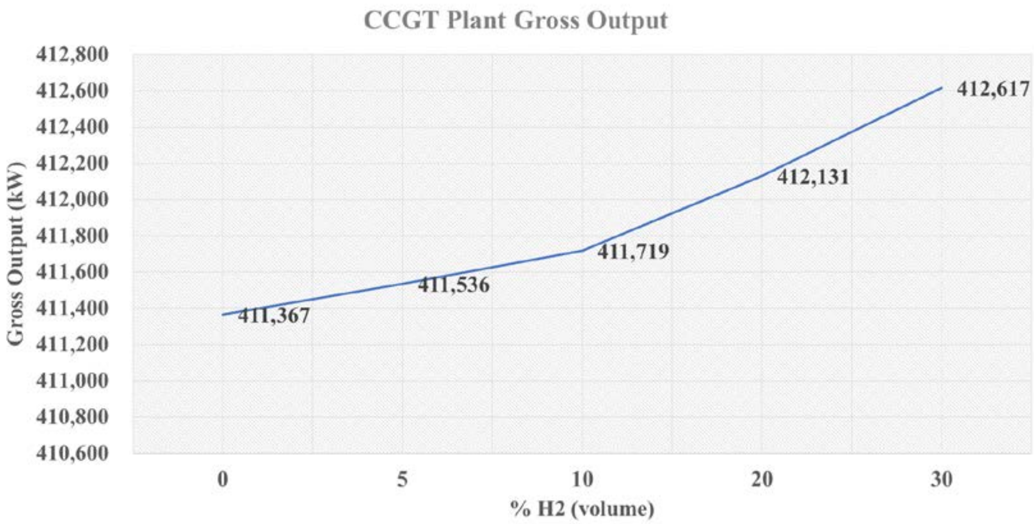

Fig. 3. CCGT Plant Gross output

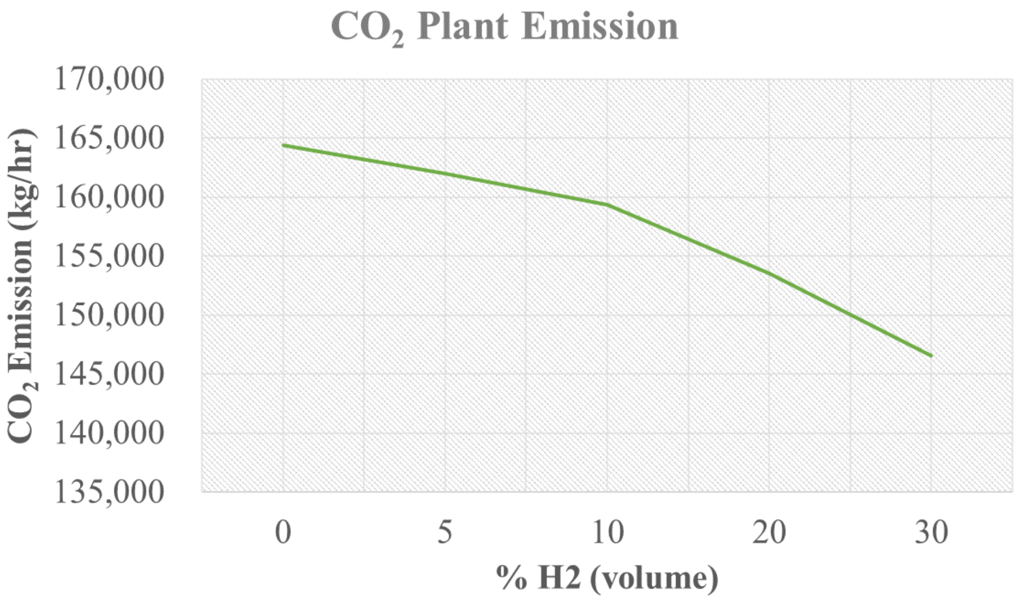

Fig 4. CO_2 plant emission

The gross output of the CCGT plant shows an increase along with the incremental mixture of H_2 composition as shown in Fig. 3 while the CO_2 emissions are decreasing as shown in Figure 4. The power output increases because the LHV of H_2 is higher compared to natural gas, so increasing H_2 will increase the LHV fuel mixture. In other studies, for hydrogen mixing and co-fire, the increase in overall power production is also observed compared to natural gas firing is also observed [34]. The increased proportion of H_2 reduces CO_2 emission because the combustion reaction of H_2 will result in H_2O. The performance parameter of the CCGT plant is summarized in Table 6. Net plant efficiency, losses, and heat rate are not affected by incremental increase in H_2 composition in the cofiring mode. The reduction in CO_2 emission for the 30% H_2 combustion volume is 10,81%. These findings are similar to the findings in other studies conducted by other researchers [34] and technology providers [2], which are in the range of 10 to 13%.

Table 6. CCGT Plant Performance

Performance	Unit	H_2 Percentage (volume)				
		0	5	10	20	30
Gross Output	kW	411,367	411,536	411,719	412,131	412,617
Net Output	kW	402,774	402,943	403,124	403,533	404,017
Net Efficiency	%	48.98	48.99	49.00	49.02	49.04
Auxiliary Power	kW	8,593	8,594	8,595	8,597	8,600
Losses	%	0.51	0.51	0.51	0.52	0.52
Net Heat Rate	kJ/kWh	7,349	7,348	7,347	7,344	7,341
Turbine exhaust mass flow	kg/s	474.30	474.30	474.20	474.00	473.80
CO2 Emissions	kg/hr	164,379	161,968	159,370	153,523	146,606

4 CONCLUSION

A benefit of gas turbines in the transition to a decarbonised world is that they can be converted for operation on new fuels, such as those with a greater hydrogen component, to support the increasing proportion of intermittent renewables in the electric grid. Changing to a fuel with a greater hydrogen concentration may require adjustments to the gas turbine, gas turbine accessories, or the rest of the facility. The necessary adjustments are proportional to the hydrogen content of the fuel. Thermodynamic modeling shows that plant production rises with the addition of H_2 to the combustion mixture, but CO_2 emissions decrease.

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