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Impact of Hydrogen Enrichment on Natural Gas Co-Firing in Gas Turbines

Muhanned Sal. Mohammed[1], Rafid M. Hannun[2]

[1,2]Department of Mechanical Engineering, Faculty of Engineering, University of Thi-Qar, Nassiriyah, Iraq.

[a]Ministery of Water Resources, State Commission of Dams & Reservoirs, Baghdad, Iraq

Corresponding Author: muh.s.m@utq.edu.iq

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Abstract

Carbon emissions from power plants represented a significant challenge as a one of primary driver of global warming. Given that hydrogen combustion in air produces no carbon emissions, coupled with its unique properties, blending hydrogen with natural gas represents an innovative step toward reducing emissions and enhancing plant performance. Hydrogen takes a significant part in mitigating carbon emissions when blended with conventional fossil fuels. Most carbon emissions of the electrical sector are from gas turbines that typically adopt natural gas, so usage fueled by hydrogen-natural gas blending is a potential path to increase the reduction of carbon emissions, which significantly impacts climate change and global warming. This study examined the effects of blending hydrogen gas with natural gas on gas turbine performance. Reducing CO_2 emissions, and the depletion of natural gas is being lowered, which are important outcomes of this technique. Therefore, this research paper investigates the impact of hydrogen addition in a real-world power plant and compares various hydrogen injection scenarios to provide a clear vision for researchers and stakeholders in this field.

Introduction

Typically, the increase in carbon emissions is accompanied by adverse climate changes such as global warming, which is one of the most significant. Paris Climate Accords mandated focusing the efforts regarding the reduction of carbon emissions, which must be about 50% in 2030 [1]. In Iraq, the carbon emissions achieved by the electrical sector that is fueled by fossil fuel rose from 26 $MtCO_2$ to 98 $MtCO_2$ through the period 2000-2023 [2]. In April 2022 carbon emissions from gas turbine plants reached 60.9% of the emissions from electrical production in Iraq. Therefore, the current situation of gas turbine plants is far from the development sustainable goals (DSGs) due to the depletion of hydrocarbon wealth in addition to causing a lot of carbon emissions [3]. The reduction of carbon emissions in electrical power generation requires reintroducing valuable solutions to the energy trilemma, which are affordable, reliable, and sustainable. The optimal technique for those challenges is collecting many sources of energy in one system to integrate the performance between them [4].

Figure 1: Energy Trilemma Triangle [4].

In gas turbines, there are two approaches to increasing the reduction in carbon emissions: pre-combustion and post-combustion, as shown in Figure 2. The pre-combustion manner is the more effective approach, which is represented by using neutral fuels such as hydrogen, synthetic methane, ammonia, and biofuels due to the gas turbines being characterized by their readiness for fuelling by more than one type of fuel. Natural gas is the traditional fuel that is used in most gas turbines, so it's considered the standard fossil fuel of gas turbines [4].

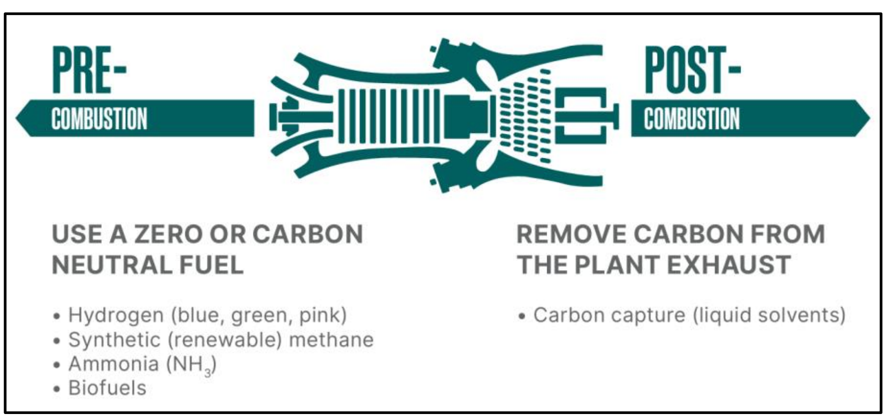


Figure 2 :Approaches to the reduction of carbon emissions in gas turbines [4].

Hydrogen gas represents the promised alternative to the gas turbine because it is characterized by several properties against natural gas, such as the lowest energy content by volume, the highest flame temperature, and the highest flame speed. In addition, water is the only burning product without carbon emissions [5]. However, It is expected that the electrical power generated by gas turbines using hydrogen will reach 65% in 2030. Currently, about two-thirds of announced electrical production projects worldwide focus on using hydrogen. The highest hydrogen share varies by gas turbine model, as shown in Table 1 [6].

Table 1: The highest hydrogen share for several gas turbine types [6].

Model of a gas turbine	Maximum share of Hydrogen (%vol.)
SGT5-4000F , and 7EA	60
GELM6000	44
M501G	20.9
SGT6-6000	38.8

For introducing a comprehensive understanding of the current situation about co-firing by hydrogen and NG in gas turbines, it is essential to highlight the previous research that addressed the matter. The following paragraphs summarize several related research studies.

G.E. Marin et al [7] investigated the combustion of pure hydrogen in a GE6FA power gas turbine of (40-77) MW and modeled it by using the ASGRET software. The research found that the consumption of fuel, air, and the heat value of exhaust gases depended on the load. The result showed that when operating on hydrogen, the efficiency of the gas turbine does not change depending on the load. Additionally, to operate on pure hydrogen, it is necessary to adjust the automatic control system, and less fuel consumption is required; however, this will lead to a serious modernization of the gas turbine.

Shanazar Allakulyyev et al. [8] proposed that the utilization of a hydrogen/natural gas mixture in a gas turbine power plant under the condition of Turkmenistan, the model of gas turbine was GE LM6000 with power 127.1 MW, and the fuel consumption at normal conditions is 7.7 kg/s of natural gas; the hydrogen share ranged from 1 to 20% by volume in 1% increments. The GTI simulator with a Mark***VI*** control program was used in this simulation. The results emphasized that when blending 10% volume of hydrogen, the consumption of blending fuel was 6.219 kg/s, while blending 20% hydrogen, natural gas consumption was reduced by 19.233%. For 20% hydrogen, the consumption of blending fuel was 5.216 kg/s, resulting in a 32.259% saving of natural gas. It was obtained that using pure hydrogen (100% by volume) as fuel needs a full rebuilding of the gas turbine, which leads to additional cost. Therefore, the hydrogen blending up to 20% used in the gas turbine in Turkmenistan doesn’t need any changes to the existing design.

Duy-Tan Vo et al. [9] investigated the combustion characteristics of a methane/hydrogen blend (0-40% hydrogen by volume) under constant heat input. The premix-combustor has an innovative design that is motivated by the backward-facing step phenomenon and generates a double recirculation zone at the bend area and pilot zone, acting as flow accelerators to stabilize the flame and prevent flashback by maintaining a low fuel concentration buffer zone between injectors and ignition points. In this study, three-dimensional RANS equations are applied as governing equations using ANSYS Fluent software. They concluded that the backward-facing step design creates good recirculation and an effective, stable flame. Perfect distribution of injectors can improve the mixing process and, in turn, amplify flame stability and reduce emissions. It is also noticeable that the combustor exhibits stable flame operation with hydrogen increasing up to 40%; the relation between lowering of carbon emissions and share of hydrogen is nonlinear, and it is about 16.7% of scenario 40% hydrogen. Flame speed beside the wall is 0.75 m/s and the highest is 1.5 m/s.

Ruly Bayu Sitanggang [10] evaluated the performance and environmental impacts of a combined-cycle gas turbine (CCGT) plant using N.G. enriched with hydrogen, with a hydrogen volume fraction between 0% and 30%. The CCGT has a rated power of 400 MWe; it comprises two gas turbines, heat recovery, and a single steam generation unit. The modeling has been done under several constant parameters, such as ambient temperature, cooling water, humidity, turbine inlet temperature, and pressure ratio. The results of the study explained that gross power output rose from 411.367 MW at 100% N.G to 412.617 MW at 30% vol. of hydrogen; the largest reduction in CO_2 was 10.81%, occurring at 30% vol. of hydrogen. Research obtained that each net efficiency, auxiliary power, and exhaust mass modestly grew, while the net heat rate had a slight decrease. He emphasized that issues associated with hydrogen enrichment require upgrades proportional to the hydrogen rate in the fuel.

Mohammad Afiq Zubir et al. [11] examined the co-firing characteristics, including temperature and air-fuel ratio, concerning Greenhouse Gas (GHG) emissions and energy liberation to identify the optimum natural gas/hydrogen blending ratio. The model was implemented via Aspen Plus software. The combustion simulation has four scenarios: 10%, 20%, and 30% vol. of hydrogen, in addition to 100% N.G. The analysis was conducted under varying conditions, with the temperature ranging from 800°C to 1200°C in 100°C increments, the pressure varying from 1 bar to 5 bar in 1 bar increments, and the air-fuel ratio ranging from 1.1 to 1.5 times the theoretical air ratio. The results indicated that the temperature and air-fuel ratio were the most sensitive parameters influencing CO_2 and NOx. They obtained a scenario of 30%, which caused a decrease in CO_2 formation, even though NOx emissions slightly increased at higher temperatures. Therefore, operating at lower temperatures is preferred for controlling NOx formation. On the other hand, they found that varying the air-fuel ratio from 1.1 to 1.5 caused NOx formation to rise by 160% for the scenario of 100 N.G. and 74% for the scenario of 30%, and the energy liberation by the hydrogen mixing system was lower because of heat loss to water formed through hydrogen combustion.

Artur Harutyunan et al. [12] explored the impact of blending hydrogen with methane in a combined-cycle gas turbine (CCGT) on exergy and efficiency, as well as power. SGT5-800H with 450 MW and SST5-5000 with 120-650 MW are models of gas turbines and steam turbines, respectively. The model was performed in Aspen HYSYS under ISO conditions, with the hydrogen volume fraction ranging from 0% to 100% in 20% increments. The findings indicate that the maximum exergy destruction of the system occurs in the gas turbine combustion chamber and decreases gradually, while the system's efficiency and power output increase, along with increasing the share of hydrogen, as depicted in Figures 3 and 4. The exergy destruction amount in steam turbine components is below that of gas turbines due to control over their inlet conditions.

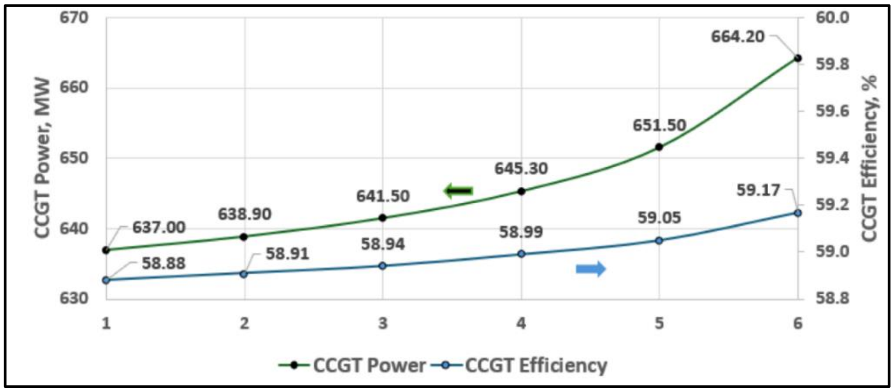


Figure 3: Effect of hydrogen share on power and efficiency [12].

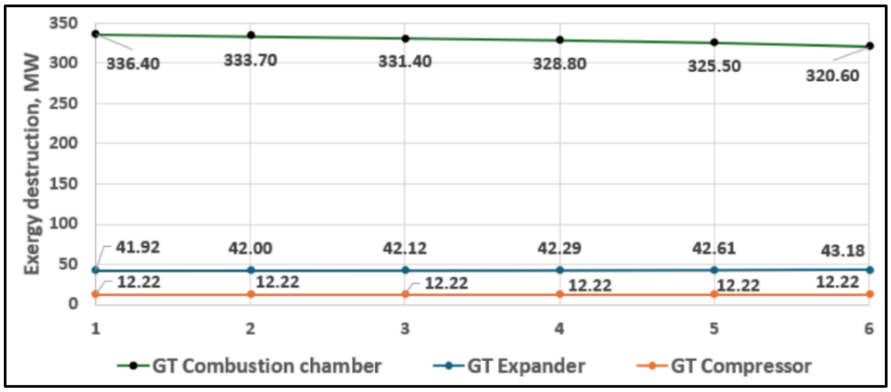


Figure 4: Effect of hydrogen share on exergy [12].

Rizcky Rashadian et al. [13] investigated the impact of adding hydrogen to N.G at different volume fractions (5%-30%, in increments of 5%) on thermal efficiency and CO_2 emissions under varying loads (100%, 75%, and 50%). They use the AspenHYSYS package to model co-firing situations in a Mitsubishi M701F gas turbine with a rated capacity of 238.5 MW. The results indicated that the thermal efficiency and the amount of CO_2 emissions are improved each 5% step of hydrogen fractions as follows: The efficiencies are 0.32% at 100% operating load, 0.34% at 75% operating load, and 0.37% at 50% operating load, and the maximum increase occurred at a 30% vol. of hydrogen scenario for all load options, while the CO_2 emission declined by 2.16% for each 5% rise in the hydrogen fraction during all operating loads. Concerning the intensity of CO_2 emissions, the researchers found it to be 0.017, 0.019, and 0.023 $kgCO_2/kWh$ at 100%, 75%, and 50% operating load, respectively.

The above studies analyzed the performance of gas turbine plants with many scenarios of hydrogen-natural gas share volume percentage. This study fills the gap of the evaluation of using green hydrogen blended with natural gas under realistic conditions of an actual gas turbine plant according to the number of operating hours regarded with the operational plan of the Ministry of Iraqi Electricity; after that, it validated the result to check its expiry. This study addresses the feasibility of blending hydrogen with natural gas for fueling a in the Thi-Qar gas turbine plant (TGTP) with a rated power of 126 MW. TCGTP is from GE and is located in Thi-Qar, south of Iraq. The goal of the study is to investigate the impact of using a blend of hydrogen and natural gas on the reduction of carbon emissions as well as to economically compare it with the base case represented by combustion with 100% natural gas.

Methodology

The plan of study is a simulation and analysis of results of five scenarios for blending green hydrogen gas with natural gas, which is required to operate one unit (GT4) of TGTP according to the load and circumstances of 2021. Figure 5 illustrates the position of TGTP located in Nasseriyha city, near the Euphrates River.

Figure 5: Location of TGTP in Nasseriyha, south of Iraq [14].

The base fuel of GT4 is natural gas (N.G.) with a density of 0.80673 kg/Nm³ under STC (at 15°C and 101.325 kPa). The composition of N.G. usage contained twelve components, but it is normalized to ensure ease in calculation. Table 2 illustrates the normalized mole fraction of major components.

Table (2) Composition of natural gas

Component	Chemical Formula	Normalized mole fraction (%)
Methane	CH_4	80
Ethane	C_2H_6	17.2
Propane	C_3H_8	1.47
Nitrogen	N_2	1.03
Carbon Dioxide	CO_2	0.3

The plan of study represented by simulation, by Aspen HYSYS, of the operation of GT4 with five scenarios (100% NG, 5% H_2, 10% H_2, 15% H_2,20% H_2, 25% H_2, 30% H_2,35% H_2, and 40% H_2) to identify the amount of fuel demanded to achieve the electrical load produced by GT4. Figure 6 depicts the layout for GT4.

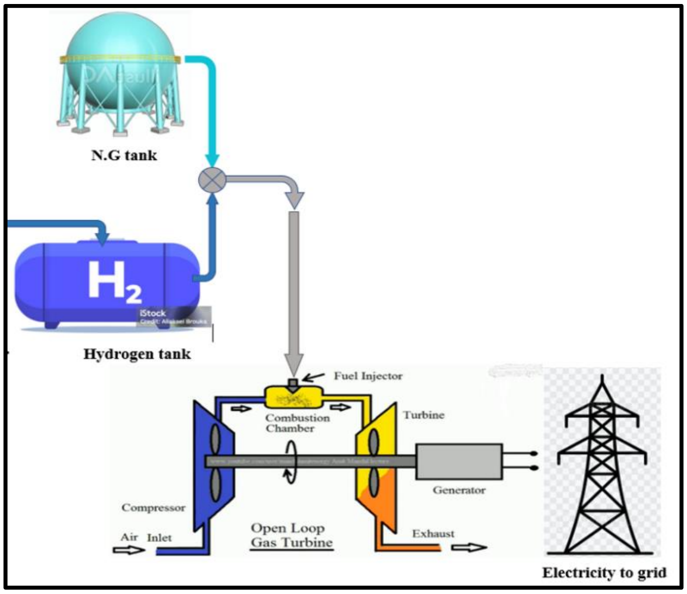


Figure 6: Schematic of blending N.G with hydrogen in GT4.

The major technical data associated with the design point under ISO conditions [15], in addition to several economic data points of GT4, have been summarized in Table 3 as a baseline to compare the results of the study with the technical and financial data.

Table (3) Technical and economic data of GT4 [16-20].

Parameter	Data
Manufacture	GE Vernova (USA)
Model	MS9001E (Frame9.E)
Power rate	126.1 MWe
Heat rate	10650 kJ/kWh
Efficiency	33.8%
Pressure ratio	12.6 bar
Air flow	407.22 kg/sec
Turbine speed	3000 r.p.m
Exhaust temperature	543 °C
Exhaust flow	421 kg/sec
Firing temperature	1124 °C
Capital cost	131.5 M$
Life span	25 years
O&M cost in 2021	4.65 M$

The operation data of GT4 during 2021 is listed in Table 4 which is in the form of monthly averages of electrical power, mass flow of N.G, thermal efficiency, exhaust temperature, and operating hours except for maintenance and forced outage of GT4.

Table 4: Operating hours, monthly load, mass flow of N.G, exhaust temperature, and thermal efficiency of GT4 in 2021 [21].

Month	Operation hours	Power (MW)	Mass flow of N.G (kg/s)	Exhaust temperature (°C)	Thermal efficiency
Jan	644	85	5.85	487	33
Feb	598	82	5.65	495	33
Mar	621	80	5.56	496	33
Apr	507	79	5.51	499	33
May	507	86	5.93	503	33
Jun	654	86	5.81	502	33
Jul	727	84	5.78	504	32
Aug	744	83	5.8	504	32
Sep	718	78	5.66	497	33
Oct	744	62	4.5	496	33
Nov	675	51.2	3.5	489	30
Dec	444	70	4.8	490	30

Figure 7 depicts the flowsheet of the Aspen HYSYS simulation of GT4 that used the Bing-Robinson equation of state because of its high accuracy for identifying thermal properties. Additionally, the Gibbs reactor was utilized to act as the combustor because of its capability of representing the gradual variation of heat inside the combustor [22].

There are several considerations to take into account through the study for simplifying the modeling, which are listed as follows:

1. The mole fraction of air components is 21% oxygen and 79% nitrogen.
2. The flow in GT4 is steady-state.
3. The heat loss in the combustor is 1% of the input heat.
4. Pressure drop in combustor is 3%.
5. The flow of hydrogen in the pipeline is steady-state, with a constant compressibility factor.
6. Lifetime of proposed plant 25 year.

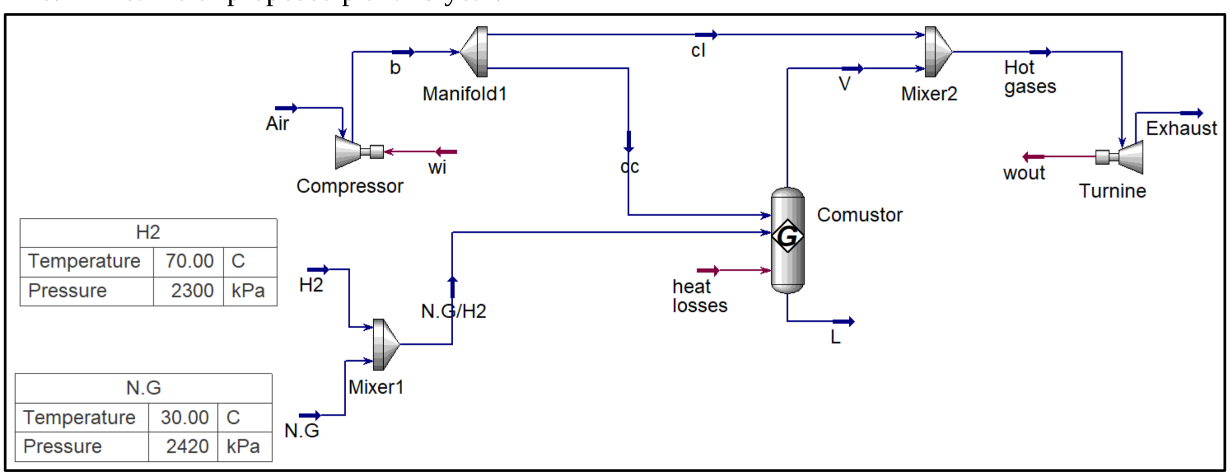


Figure 7: The flowsheet of GT4 simulation by the Aspen HYSYS

Governing equations

The mathematical framework of this study is comprised of a number of equations that regard available parameters in the right context in order to reach the resultants that lead to conducting the optimal-realistic analysis.

Energy balance in the combustor is represented by equation (1), which is used to identify the amount of air that is demanded to achieve the combustion of the fuel [23].

$$\dot{m}_f \times LHV_{fuel} = \left(\dot{m}_a + \dot{m}_f\right) h_3 - \dot{m}_f h_2 \tag{1}$$

That the performance parameter of heat rate that is determined by equation (2) represents the heat amount of the input fuel to the combustor in a gas turbine, which generates one unit of power [23] [24].

$$HR = \frac{Q_{in}}{W_{net}} \tag{2}$$

Equation (3) is used to calculate the thermal efficiency of a gas turbine, which is expressed as the overall adiabatic thermal efficiency. Mathematically, it is the ratio of net actual work produced by the gas turbine cycle to the energy that is added to the combustion chamber [24].

$$\eta_{th} = \frac{W_{net}}{\dot{m}_f\,(LHV)} = \frac{3600(kJ\ /\ kWh)}{HR(kJ\ /\ kWh)} \tag{3}$$

The air-to-fuel ratio, which is calculated by equation (4), is considered a very important indicator for adjusting the combustion of fuel, that has an impact on the emissions and power produced by the gas turbine cycle [25].

$$AFR = \frac{m_{air}}{m_{fuel}} \tag{4}$$

The equation (5) is used to determine the theoretical minimum amount of air needed to completely combust all fuel in the reaction; in other words, it represents the moles of air required to combust one mole of fuel [25].

$$AFR_{st} = \frac{\left(n + \frac{m}{4}\right) \times 32 + \left(n + \frac{m}{4}\right) \times 105.33}{n \times 12 + m} \tag{5}$$

The chemical equation (6), is the generic chemical reaction of hydrocarbon fuel when combusted by air, which is the blending of oxygen and nitrogen with mole fractions of 21% and 79%, respectively [25].

$$C_nH_m + \left(n + \frac{m}{4}\right)O_2 + \frac{79}{21}\left(n + \frac{m}{4}\right)N_2 \rightarrow nCO_2 + \left(n + \frac{m}{4}\right)H_2O + \frac{79}{21}\left(n + \frac{m}{4}\right)N_2 \tag{6}$$

The excess air expressed by equation (7), which is cross the theoretical minimum air of combustion, represents the ratio of air that doesn't take part in the chemical reaction of fuel combustion in the combustor of the gas turbine cycle, but they warm due to touch with the flame [24].

$$\lambda = \frac{AFR - AFR_{st}}{AFR_{st}} \quad (7)$$

Results and discussion

The results of the GT4 simulation prompted discussion about the effects of adding hydrogen to co-firing with N.G and about the amount of hydrogen required for each hydrogen share in the mixture fuel. This section details the technical, economic, and environmental effects of hydrogen fueling in GT4 and compares these effects with those of using pure N.G, which is typically used in existing Iraqi power plants. To ensure the accuracy and realism of the GT4 model founded by Aspen HYSYS, the simulation results were compared with reference values for several parameters, including monthly averages of electrical power, exhaust temperature, and thermal efficiency. The reference values acted as actual operating conditions for GT4 in 2021. Figure 8 displayed the variance of the simulated value from the reference value of the monthly average of electrical power, which explained that the deviation rate ranges from 0.22% to 2.7% for most months of the year, while it is 7.2% and 5.7%, a for September and October, respectively.

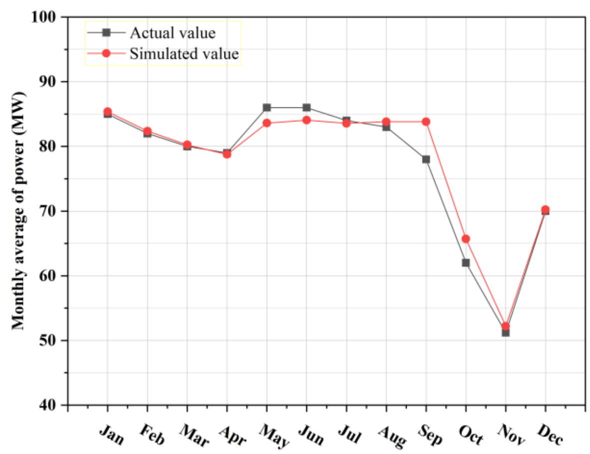


Figure 8: The deviation of the monthly average for electrical power

Regarding exhaust temperature, the largest Dispersion is about 1.4% in June, and for the rest of the months it ranges from 0.06% to 1.3%, as shown in Figure 9.

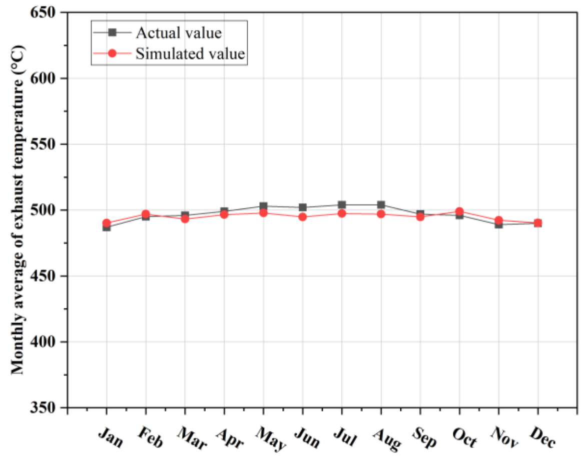


Figure 9: The deviation of the monthly average for exhaust temperature

On the other hand, the thermal efficiency deviation was obtained to be from 7.7% to 3.1% as illustrated by Figure 10.

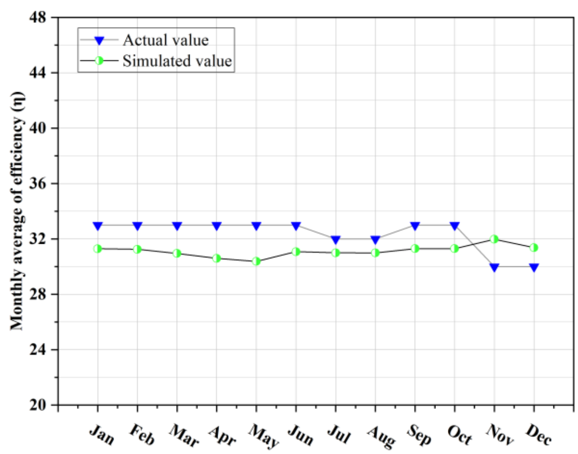


Figure 10: The deviation of the monthly average for thermal efficiency

The reasons for the deviations are associated with many assumptions, such as dry air, where the moisture of water is removed as one component of air, making the amount of dry air sucked by the compressor more than that of moist air; consequently, the compressor needs more energy to supply dynamic energy for air in addition to the expander producing a higher amount of electrical power. The change in electrical load caused the creation of the transmission stage of flow, which is a misalignment of steady-state flow. Another reason for the deviation related to the nature of fuel, N.G., that was used in the simulation was the assumption of five components, while neglecting those with minor fractions. Human mistakes were one reason the actual data was inaccurate, as it was recorded manually.

Table (5) displayed the monthly average of hydrogen mass flow for each share of hydrogen that matches GT4 needs at operating and weather-related conditions in 2021.

Table 5: Monthly average load of hydrogen (kg/sec) of GT4.

Month	Share of hydrogen							
	5%	10%	15%	20%	25%	30%	35%	40%
Jan	0.0320	0.0667	0.1042	0.1450	0.1894	0.2380	0.2915	0.3505
Feb	0.0309	0.0644	0.1006	0.1400	0.1829	0.2299	0.2815	0.3385
Mar	0.0305	0.0634	0.0990	0.1378	0.1800	0.2262	0.2770	0.3331
Apr	0.0302	0.0628	0.0981	0.1365	0.1784	0.2242	0.2745	0.3301
May	0.0325	0.0676	0.1056	0.1469	0.1920	0.2413	0.2955	0.3553
Jun	0.0318	0.0662	0.1035	0.1440	0.1881	0.2364	0.2895	0.3481
Jul	0.0317	0.0659	0.1030	0.1432	0.1871	0.2352	0.2880	0.3463
Aug	0.0318	0.0661	0.1033	0.1437	0.1878	0.2360	0.2890	0.3475
Sept	0.0311	0.0645	0.1008	0.1403	0.1833	0.2303	0.2820	0.3391
Oct	0.0246	0.0513	0.0801	0.1115	0.1457	0.1831	0.2242	0.2696
Nov	0.0219	0.0456	0.0713	0.0991	0.1295	0.1627	0.1993	0.2397
Dec	0.0263	0.0547	0.0855	0.119	0.1554	0.1953	0.2392	0.2876

The highest mass flow of hydrogen was noted in May, while the lowest was in November because the maximum monthly average of electrical power produced was in May, and the minimum was in November. The required peak electrical load produced by GT4 occurs in May, June, July, and August, which coincide with increases in ambient temperature; therefore, to meet the increasing electrical load, it was crucial to increase the fuel mass flow. That decrease in air density led to maximizing the electrical power consumed by compressors, which means additional fuel to consume, too.

Figure 11 illustrated e relation between share of hydrogen and mass flow of blended fuel across year 2021 and under the condition of constant energy of fuel at all scenarios of green hydrogen. Due to the low heating value per mass (LHV) of hydrogen being greater than that of N.G, an increasing share of hydrogen requires lowering the mass share of N.G with an amount equivalent to the LHV value of the added hydrogen, consequently, a decrease in the mass flow of blended fuel.

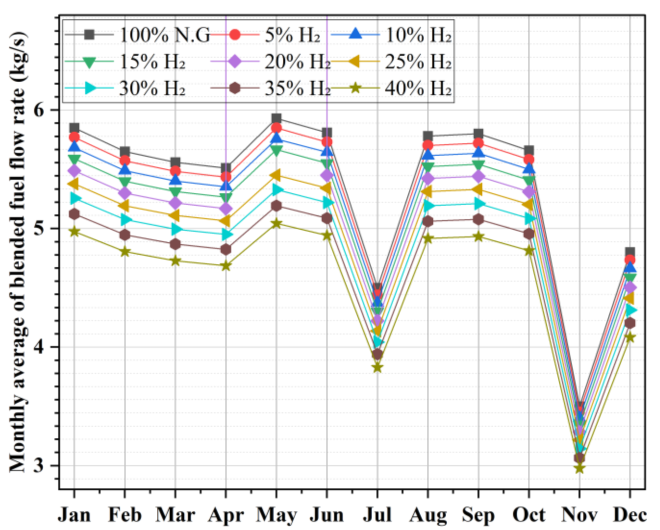


Figure 11: Influence of adding hydrogen on the mass flow of blended fuel

Using green hydrogen gas minimized the adoption of N.G in GT4; the reduction is proportional to the share of hydrogen in blended fuel. Notably, part of N.G. is imported; therefore, replacing it with green hydrogen was logical and justified. Figure 12 depicted the reduction of imported gas in each scenario after replacing it with green hydrogen, where the amount of imported N.G. in the scenario of 100% N.G. was 46554742 Nm³/year; the reduction increased continuously from 2489137 Nm³/year in the scenario of a 5% share of hydrogen to the scenario of 40% hydrogen until it became 26360990 Nm³/year.

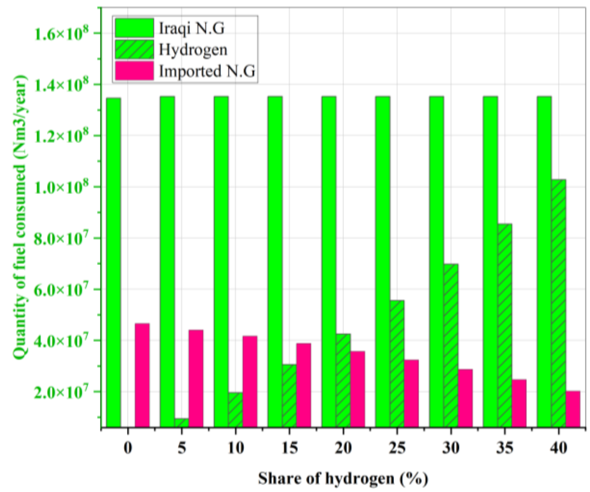


Figure 12: The reduction of imported N.G

Considering the role of hydrogen in improving the power from GT4, the role of hydrogen in increasing the electrical energy has been clearly obtained. Figure 13 displayed the enhancement in electrical energy aligning with the increased share of hydrogen in blended fuel.

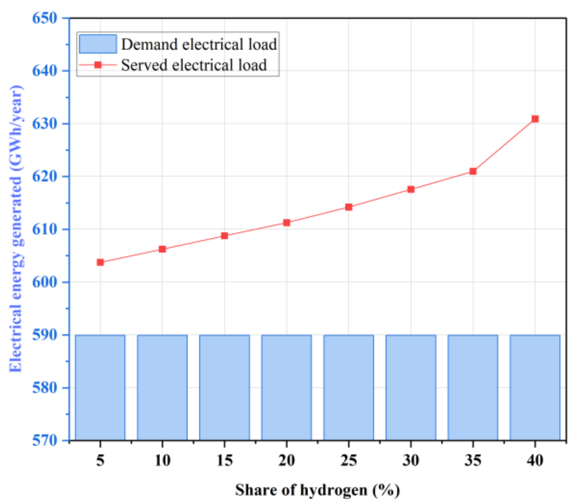


Figure 13: The impact of hydrogen on electrical energy produced by GT4

Figure 14 depicted the impact of hydrogen on the electrical power generated by GT4, where it was clarified that hydrogen slightly improved the electrical power as the share of hydrogen increased. The increase in electrical power was directly proportional to the rise in the share of hydrogen in blended fuel. The major reason for this improvement was the increase in flame temperature, which raised the enthalpy of the hot gases and the work produced by the turbine. Another reason is the decrease in power consumed by the compressor due to the mass flow of air entering the compressor, accomplished by lowering the fuel mass flow rate.

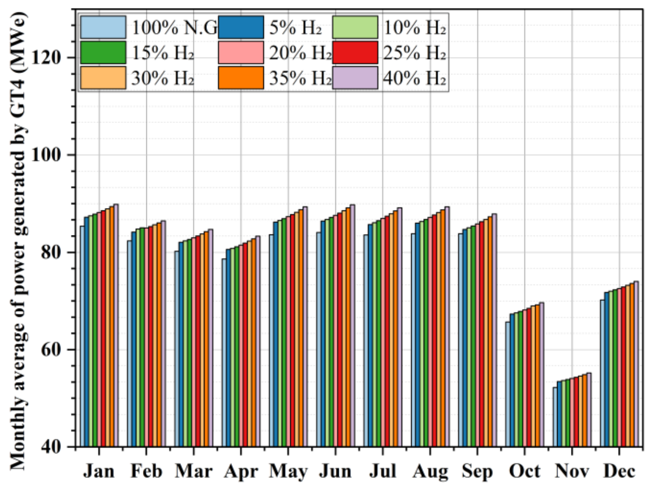
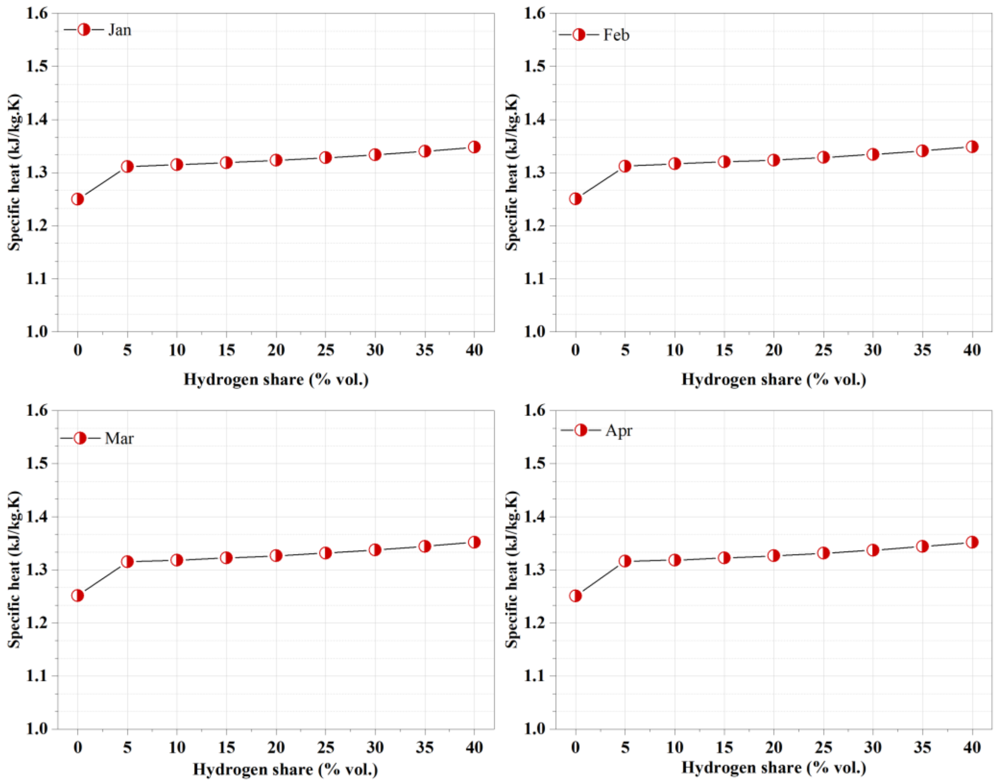
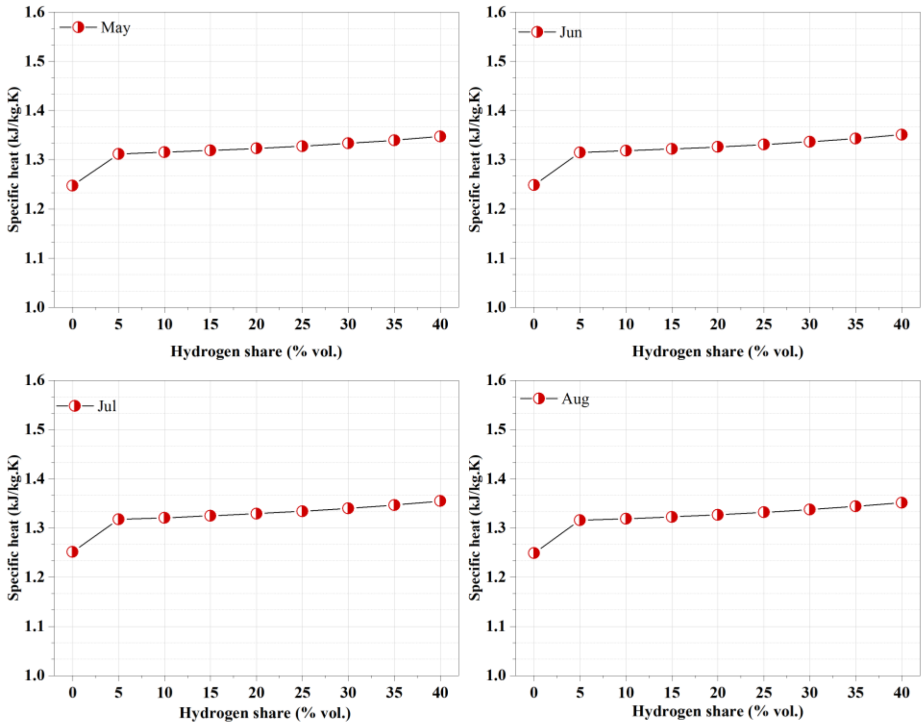


Figure 14: The impact of hydrogen on electrical power generated by GT4.

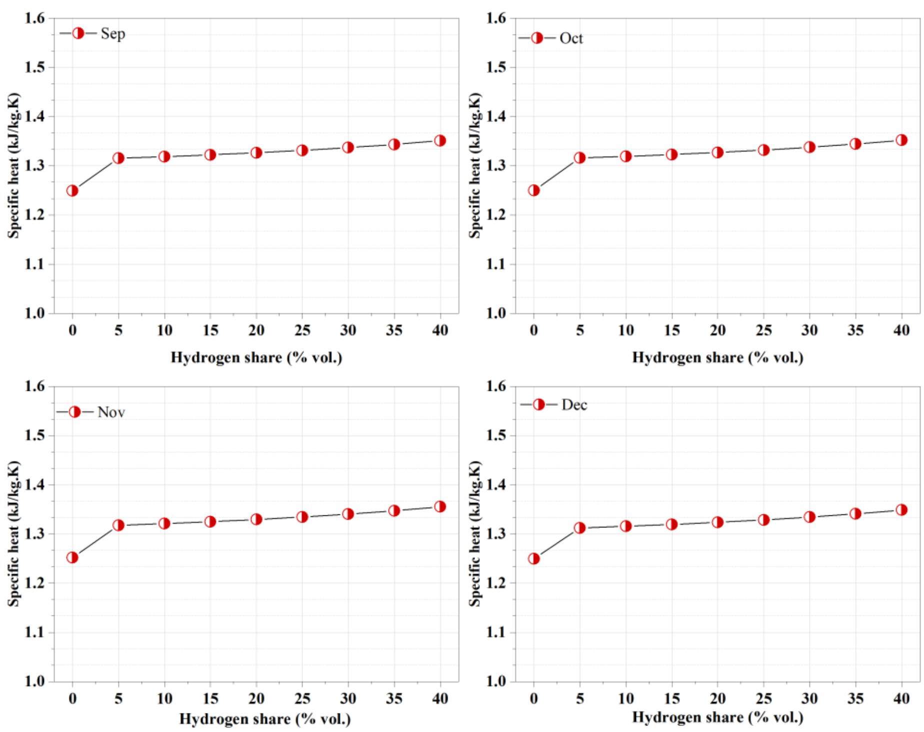
The specific heat property of hot gases witnessed a semi-uniform increase as a result of adding hydrogen due to hydrogen-burning products, steam only, which has a specific heat higher than that of carbon dioxide. In this context, Figures 15a, 15b, and 15c were explained the variation of the value of the specific heat of hot gases produced from burning hydrogen at GT4.



(a) Specific heat-hydrogen share curve for Jan., Feb., Mar., and Apr.



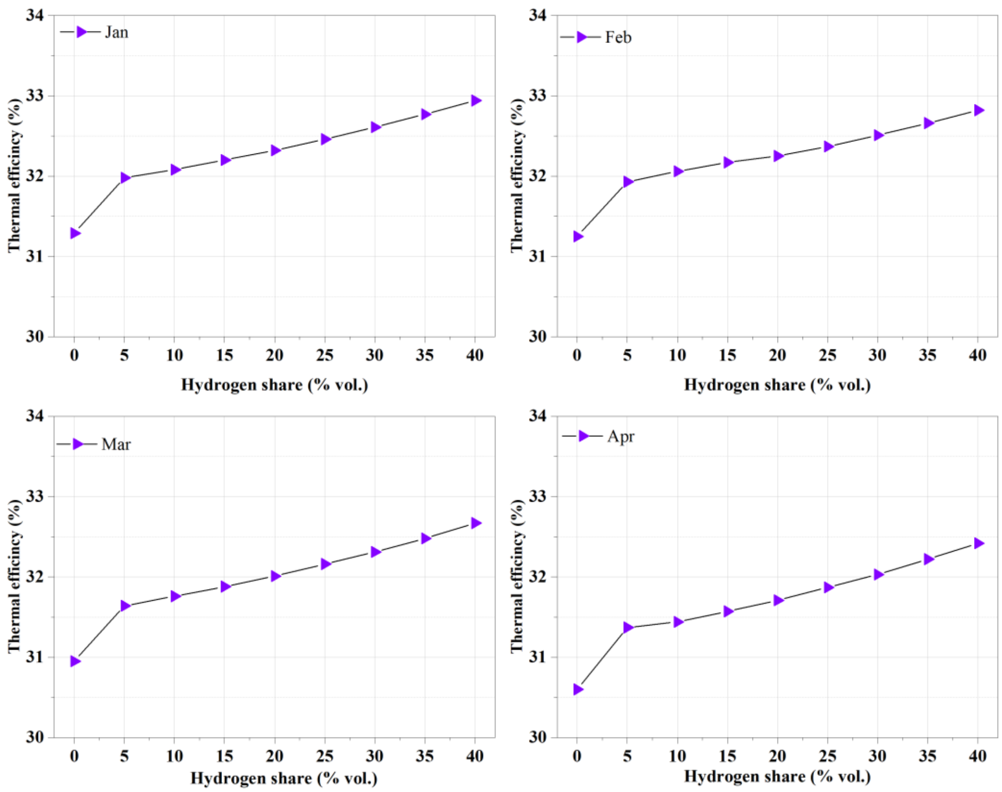
(b) Specific heat-hydrogen share curve for May, Jun., Jul., and Aug.



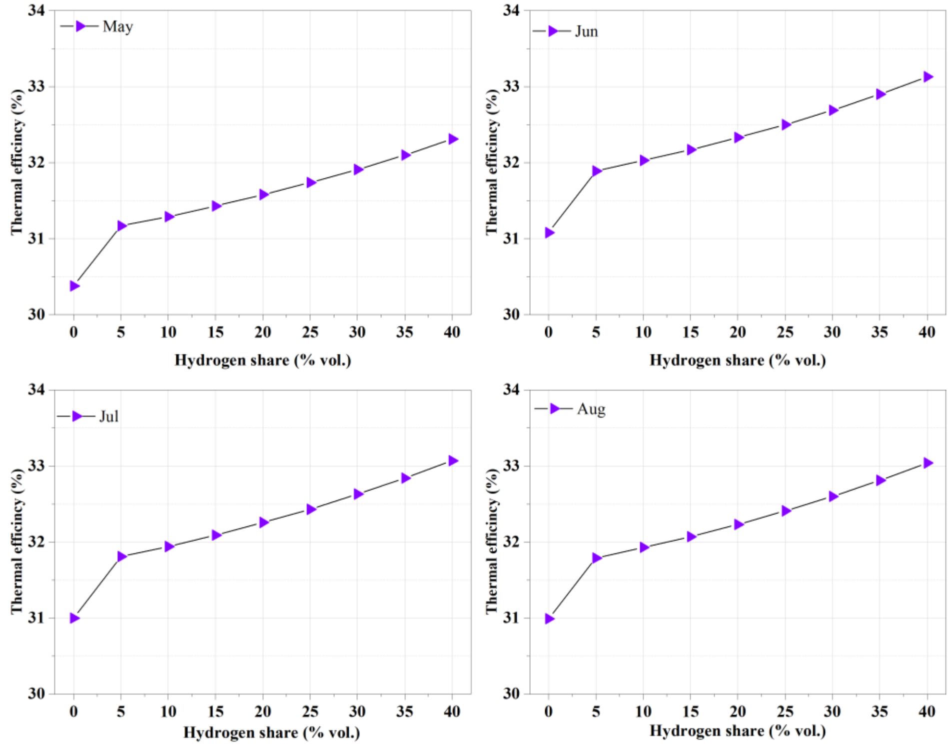
(c) Specific heat-hydrogen share curve for Sep., Oct., Nov., and Dec.

Figure 15: The impact of hydrogen on the specific heat of blended fuel

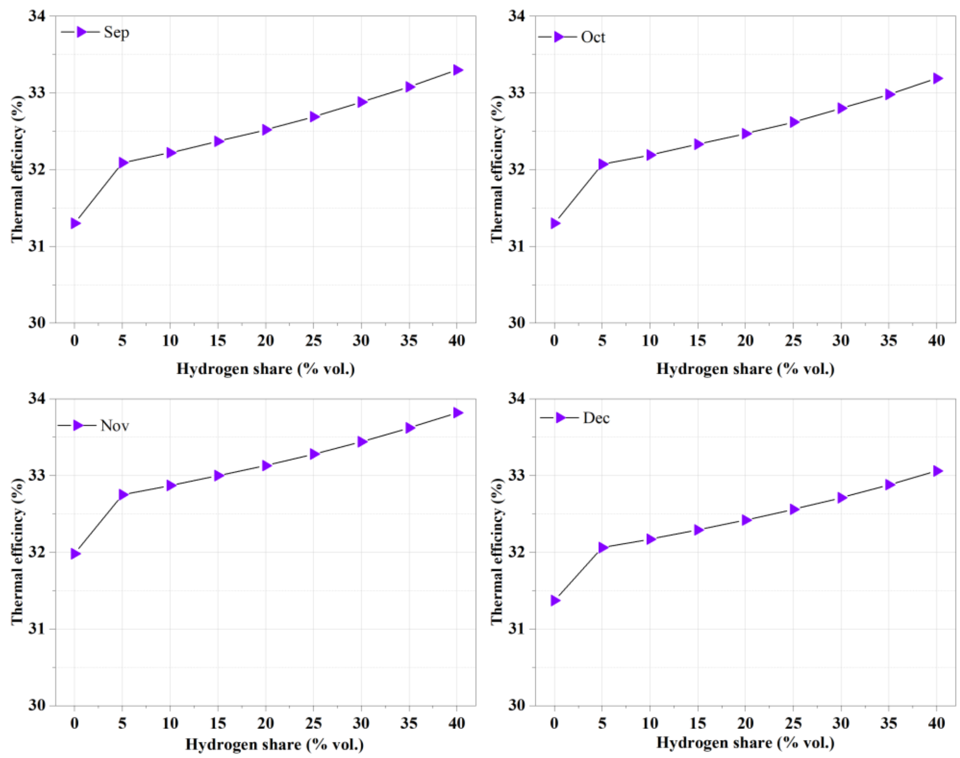
Figures 16a, 16b, and 16c were exhibited the situation of thermal efficiency in both with and without hydrogen; high combustion speed and diffusivity of hydrogen helped to convert the largest amount of fuel into work; the high flame temperature of hydrogen led to its rise in the mixture; and the value of specific heat of hot gases was higher without hydrogen products of blended fuel due to its containing steam and a smaller amount of carbon dioxide. All these factors resulted in better combustion and justified the enhancement of thermal efficiency. Additionally, the wide flammability range of hydrogen is considered a key factor of improving the thermal efficiency due to it permitting the blended fuel to continuously burn under conditions of lean combustion, to be more stable, and to reduce the amount of bleed air.



(a) Thermal efficiency-hydrogen share curve for Jan., Feb., Mar., and Apr.



(b) Thermal efficiency-hydrogen share curve for May, Jun., Jul., and Aug.



(c) Thermal efficiency-hydrogen share curve for Sep., Oct., Nov., and Dec.

Figure 16: Monthly average of thermal efficiency of GT4

There is noted in the first addition of 5% hydrogen, which greatly changed the chemical components of the combustion products, resulting in a significant change in characteristics, while the rest of the hydrogen addition iterations did not produce any new products, but it improved the combustion characteristics due to the features of hydrogen gas.

Figure 17 demonstrates the maximum and minimum annual amounts of NOx emissions were 13894 tons and 11055 tons, respectively, whereas the reference case at 100% N.G. was 12942 tons. The annual increase was directly proportional to the rise in hydrogen share in blended fuel because of the adiabatic flame temperature excess of 1400°C, which represents the threshold temperature that led to the formation of NOx by the thermal approach. Additionally, that could be observed the annual amount of NOx dramatically decreased with the addition of 5 vol.% of hydrogen, where the key factor in this decrease was the adiabatic flame temperature did not reach the threshold temperature and partially due to the reduced carbon content during hydrogen enrichment.

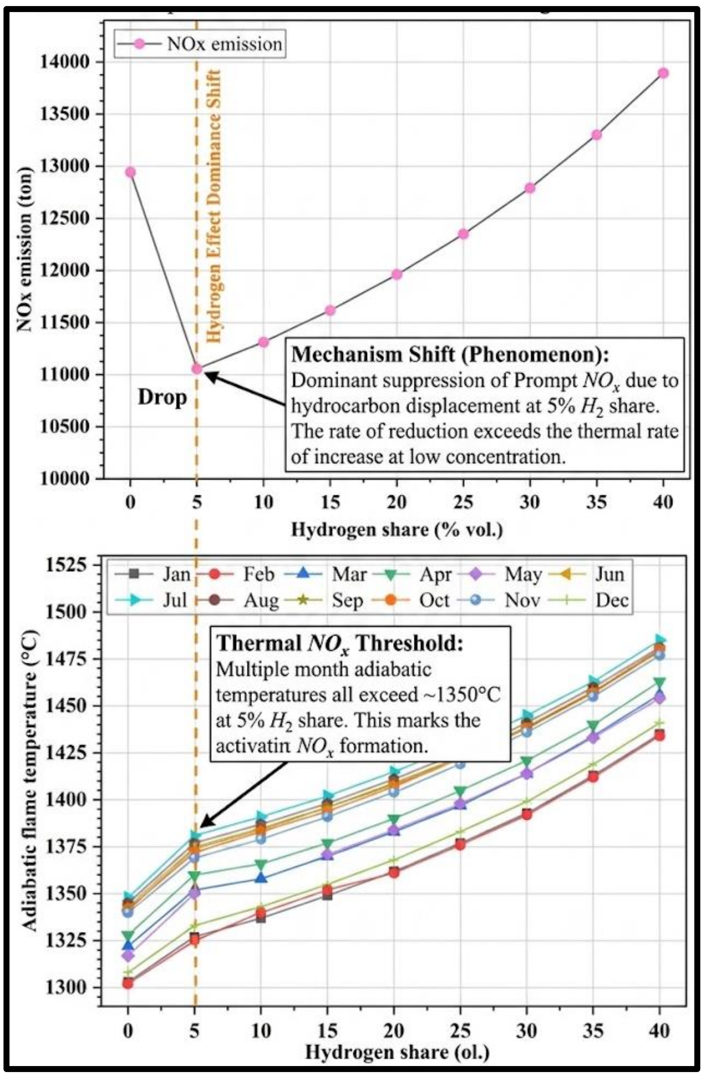
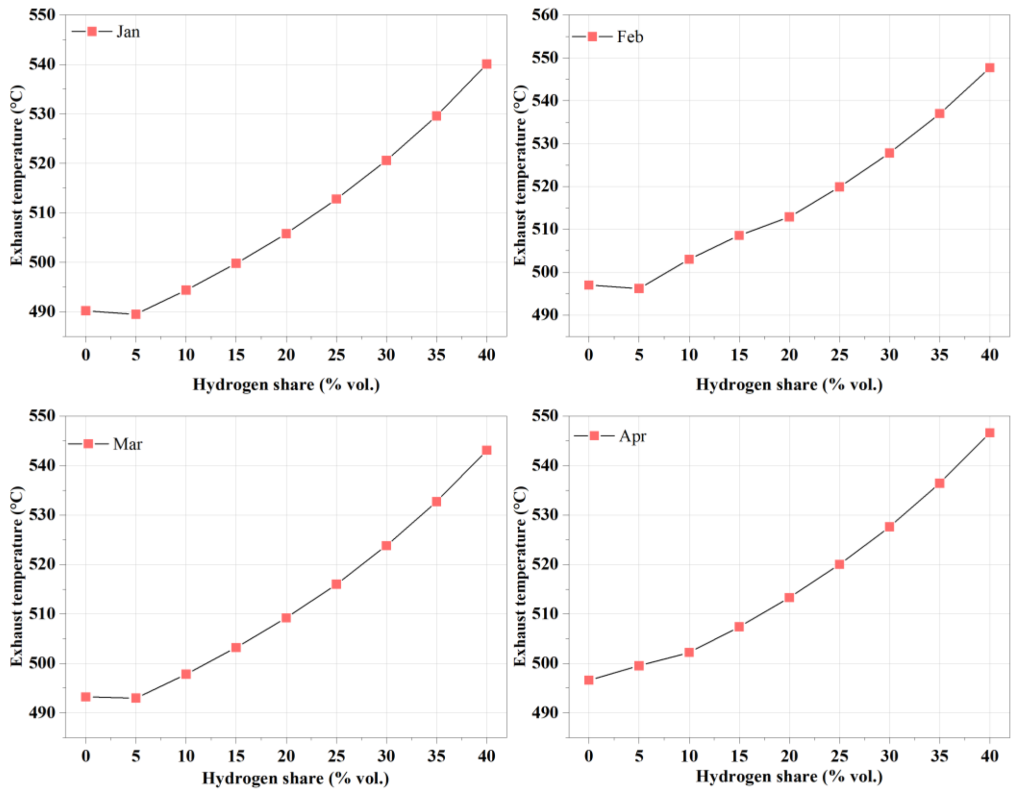
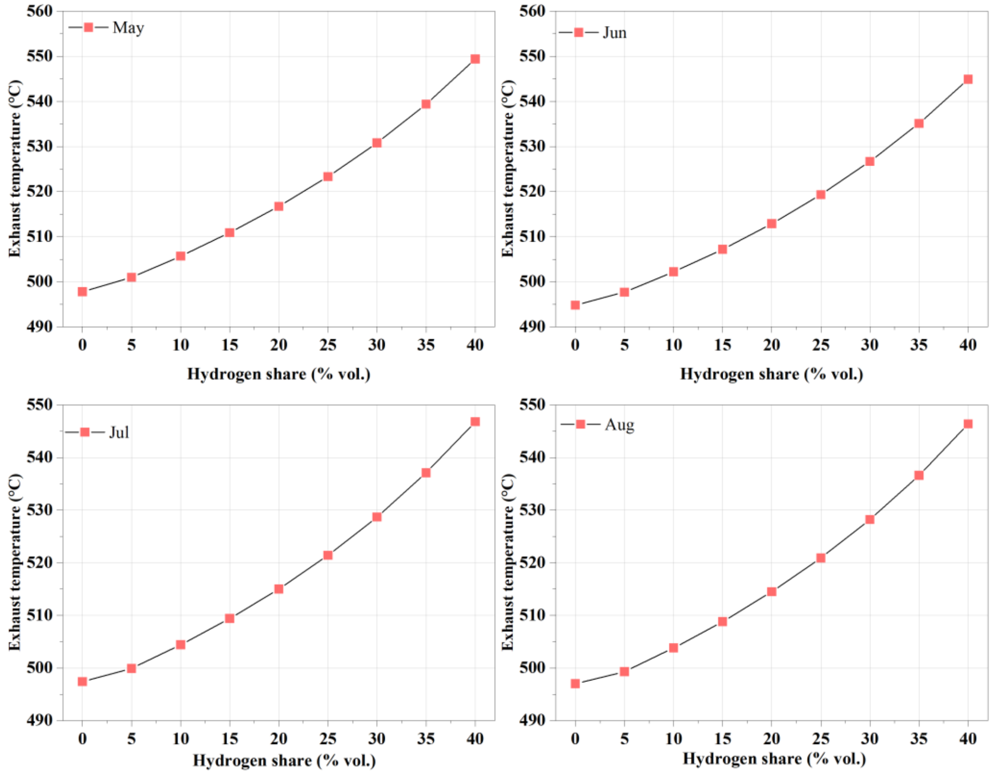


Figure 17: Annual NOx emissions and adiabatic flame temperature.

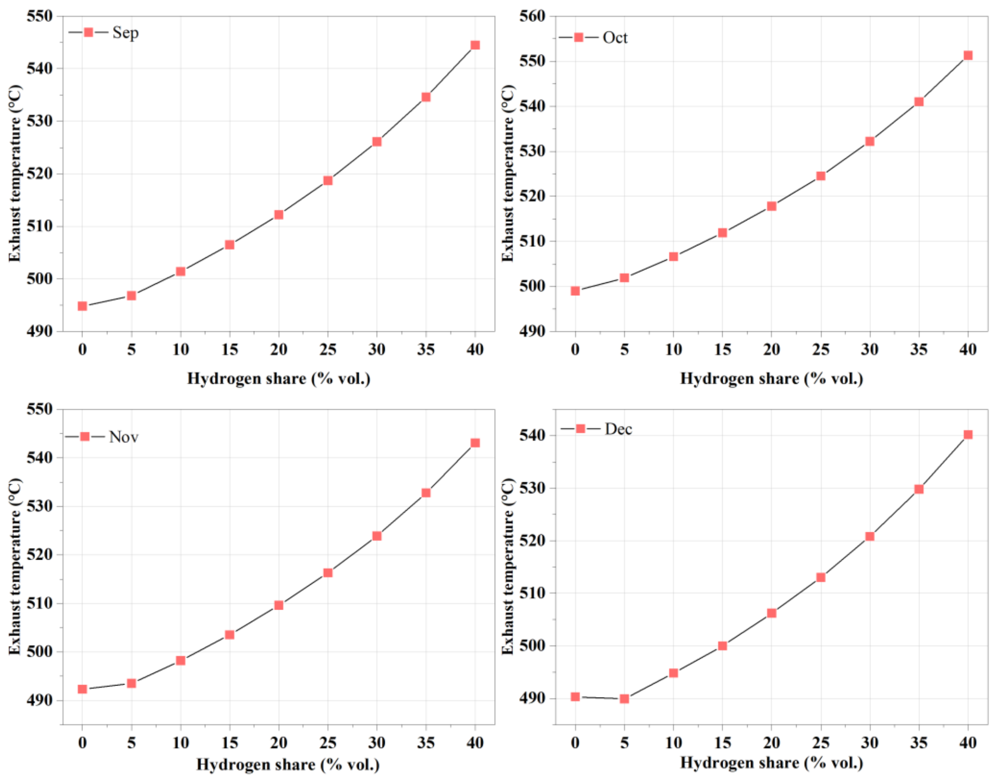
The results exposed the influence of hydrogen enrichment on the temperature of exhaust, where the temperature took to growth gradually due to the high temperature and specific heat of hot gases, which made the exhaust gases carry more heat than pure N.G fuel. In this context, the highest monthly average temperature of exhaust is obtained in the 40% hydrogen scenario, where it ranges between 540°C and 551°C, and the lowest in the 5% hydrogen scenario, where it falls between 489°C and 500°C, as shown in Figures 18a, 18b, and 18c.



(a) Exhaust temperature-hydrogen share curve for Jan., Feb., Mar., and Apr.



(b) Thermal efficiency-hydrogen share curve for May, Jun., Jul., and Aug.



(c) Thermal efficiency-hydrogen share curve for Sep., Oct., Nov., and Dec.

Figure 18: Monthly average of the temperature of exhaust gases emitted from GT4

It was observed that declining CO_2 emissions increased each time the share of hydrogen in blended fuel rose, due to the reaction between green hydrogen and oxygen that is found in air, which does not contain carbon. Figure 16 explained the amount of CO_2 reduction of GT4, starting from 5647 tons/year in the scenario of 5% hydrogen to 59824 tons/year in the scenario of 40% hydrogen. In other words, the overall level of CO_2 emissions decreased by 1.41% in the 5% hydrogen scenario, and it continues to increase until it reaches 14.9% in the 40% hydrogen scenario.

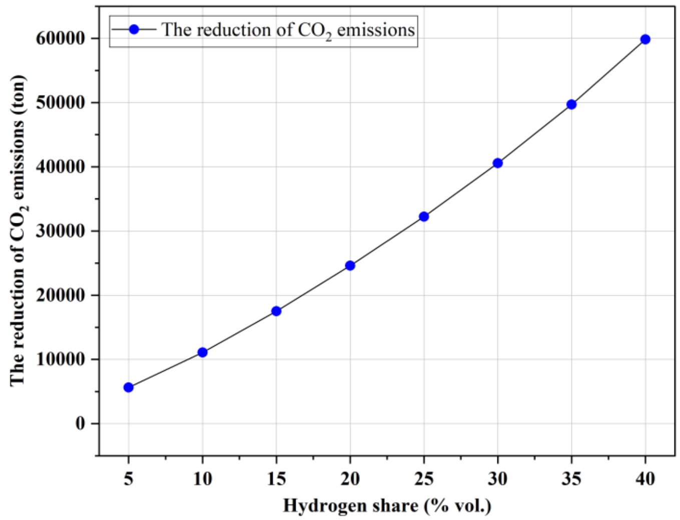


Figure 16: The reduction of CO_2 emissions.

Conclusions:

This study introduces the clear insights of potentially utilizing hydrogen as fuel for power generation under conditions of Thi Qar Province, south of Iraq. The model effectively explains the advantages and disadvantages of using blended hydrogen with N.G in gas turbines, particularly in terms of efficiency, emissions reductions, and operational expenses. The results are encouraging; they focus on replacing imported N.G with green hydrogen. The study lists the major conclusions as follows:

- Utilizing hydrogen in gas turbines has a significant clean path to reduce carbon emissions that result from the electrical energy generation sector. Therefore, it requires more intensive research, interest, and support.
- NOx emissions decrease initially, shifting to hydrogen; thereafter, they increase in proportion to the hydrogen share, with a 30% hydrogen share considered the critical limit for redesigning the combustor to address the large amount of NOx formed by hydrogen enrichment.
- Given the unique combustion characteristics of hydrogen, hydrogen enhances the combustion characteristics of natural gas mixtures, which enhances power generation, thermal efficiency, and the specific heat of hot gases.
- Hydrogen enrichment was achieved by reducing the fuel mass flow because hydrogen has a higher LHV than N.G fuel.

For fueling by a greater share of hydrogen, it is essential to upgrade parts of the gas turbine, especially the combustor, to avoid damage due to the high flame temperature resulting from hydrogen burning.

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