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# Energy Performance of Gas Turbine Compressor Stations Operating With Hydrogen–Natural Gas Blends

*Hydrogen is a rising energy carrier for decarbonization. One possible use is blending it with natural gas, but researchers must address performance issues in thermal systems. In this study, we evaluate the performance of a natural gas compression system with a gas turbine using energetic, exergetic, and exergoeconomic analyses for different hydrogen–natural gas blends. The analyses reveal a reduction of 187.5 kg CO<sub>2</sub> per ton of fuel for every 10% increase in hydrogen content. Furthermore, air and fuel requirements decrease by 15%, while compression train energy efficiency improves by 27.21% in certain blends. However, the specific cost of gas rises to \$20.56/GJ when using pure hydrogen. Finally, increasing the hydrogen fraction reduces CO<sub>2</sub> emissions but also raises costs.*

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## Introduction

Hydrogen is a clean energy carrier that reduces pollution and improves efficiency across various sectors, including transportation and residential power generation [1]. Meanwhile, gas turbine compressor stations are essential to the energy industry and climate change mitigation. First, they enable natural gas transport through pipelines, making their performance critical [2]. Second, reducing NO<sub>x</sub> emissions in gas turbines is vital due to their harmful effects on both the environment and human health [3]. Therefore, the use of hydrogen in gas turbine systems raises questions about its impact on the performance of compressor stations. Optimizing

efficiency and reducing environmental impact requires understanding how these stations perform with hydrogen–natural gas blends.

Praveen Kumar et al. [4] examine the performance and emission characteristics of karanja biodiesel blends enhanced with green hydrogen fuel and nanoparticles, revealing significant improvements in engine efficiency and emissions. The modified blends achieve higher brake thermal efficiency and lower brake-specific fuel consumption than conventional diesel. The results confirm that hydrogen enrichment enhances fuel performance and reduces emissions in energy conversion systems, although nitrogen emissions increase or remain unchanged, as confirmed by Anand and Debbarma [5].

Wang et al. [6] conducted a numerical simulation on the combustion characteristics of methane–air mixtures influenced by a hydrogen jet, offering insights relevant to gas turbine compressor stations operating with hydrogen–natural gas blends. The study

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demonstrates that hydrogen injection enhances combustion efficiency, addressing challenges in low-concentration methane ignition, which is crucial for improving turbine performance. Optimizing the timing of hydrogen injection reduces waste gas production and increases combustion speed, contributing to greater fuel efficiency and stability in gas turbine operations. Additionally, the observed transition from a premixed flame to a jet flame highlights key combustion dynamics that impact flame stability and emissions control in hydrogen-enriched gas turbines. These findings suggest that hydrogen–natural gas blends can enhance gas turbine compressor station efficiency, reduce carbon emissions, and support cleaner energy solutions in natural gas infrastructure.

Peng et al. [7] found that increasing the amount of hydrogen in a hydrogen–natural gas mixture from 0% to 30% decreases the pressure ratio by 18.9%, and the shaft power decreases by 28.6% in centrifugal compressors. Injecting hydrogen into natural gas causes the compressor's surge range to increase, narrowing the stable range.

Guo et al. [8] investigated the impact of three key operating factors on the two-piston compressor performance of a novel integrated system. The authors identified the optimal operating values using the Taguchi method when compressing hydrogen from 12 to 45 MPa. The time ratio of piston A's movement primarily determines energy consumption and specific consumption. In contrast, the rising time ratio of piston B had the greatest impact on the delivered mass. The optimal combination was 0.4 for the movement time ratio of piston A, 0.45 for the ascending time ratio of piston A, and 0.5 for the ascending time ratio of piston B. Under optimal operating conditions, the lowest specific energy consumption is 2733.75 kJ/kg.

Ren et al. [9] studied the performance of a 90-MPa diaphragm compressor used in hydrogen filling stations to regulate hydraulic oil temperature. Their experimental results demonstrated that lowering oil temperature significantly improves compressor volumetric efficiency and reduces discharge temperature. In the test case, decreasing oil temperature from 95 °C to 35 °C increased volumetric efficiency from 36.2% to 43.5% and lowered discharge temperature by 49 °C.

Jin et al. [10] conducted a numerical study on two-phase flow and heat transfer characteristics in an ionic liquid compressor for hydrogen refueling stations. The results revealed that hydrogen–ionic liquid interaction intensified due to input shock and piston reciprocation, destabilizing the phase interface and causing fragmentation. This process formed abundant hydrogen bubbles and ionic liquid droplets, which significantly increased the two-phase heat transfer area and relative velocity, enhancing heat transfer. At the recommended frequency of 5 Hz, hydrogen temperature increased by 55.69 K during compression, and the polytropic index reached 1.114, closely approaching an isothermal process.

Hamedi et al. [11] conducted a techno-economic analysis and developed an optimization model for extracting H<sub>2</sub> from natural gas distribution networks. Their results highlighted that extracting H<sub>2</sub> from a 12-bar distribution network with a 30% H<sub>2</sub> and 70% CH<sub>4</sub> mixture by volume led to costs of \$0.8064/kg-H<sub>2</sub> and \$0.9012/kg-H<sub>2</sub> for product purities of 99.00% and 99.97%, respectively. However, the study focused solely on extraction, emphasizing its economic feasibility without addressing compression costs for hydrogen–natural gas mixtures.

Olayini et al. [12] conducted an exergetic and economic evaluation of replacing natural gas with hydrogen–natural gas blends in gas-fired power plants, offering valuable insights for gas turbine compressor stations operating with these blends. The study, based on simulations using EBSILON Professional, assessed five power plants across different countries, demonstrating that hydrogen integration reduces carbon emissions while enhancing energy and exergy efficiencies without compromising net power output. However, the introduction of 20 vol% H<sub>2</sub> led to a 16% increase in NO<sub>x</sub> emissions and fuel volumetric flowrate, impacting design parameters in hydrogen-enriched gas turbine systems. Additionally, the levelized cost of fuel varied depending on the price disparity between hydrogen and natural gas, highlighting

economic constraints for large-scale implementation. These findings are crucial for gas turbine compressor stations, where hydrogen–natural gas blends could improve efficiency and sustainability, but require modifications in combustion dynamics, emission control, and fuel delivery systems to ensure optimal performance.

In this study, we analyze the effects of different hydrogen–natural gas mixtures on energy, exergetic, and exergoeconomic variables in a fuel gas compression station with a gas turbine. We establish a calorific potential of 168,485 m<sup>3</sup>/day at 6307 kPa for all evaluated process gas mixtures.

## Materials and Methods

The gas turbine compressor assembly (Fig. 1) compresses gaseous fuel and obtains primary energy from the same gaseous fuel. It features a SolarTurbines TAURUS 60 gas turbine with an output of 5740 kW and a nominal efficiency of 32%. The compressor is a 12-stage Solar C33 with a maximum total head of 257 kJ/kg and an isentropic efficiency greater than 80%. This unit intakes gas at 2652.4 kPa and raises the pressure to a discharge of 6444.5 kPa. The system also includes 2.25 kW Air-X Changers air coolers, ensuring the gas meets the required temperature limits before entering the conveying system.

### The Properties of the Fuel Mix Natural Gas and Hydrogen.

In this case, we calculate the higher heating value of a fuel mixture by summing the products of the volumetric fractions and their respective higher heating values. The same method applies to determining the lower heating value and molecular weight of the mixture (Eq. (1)–(4)) [13].

$$MW_{\text{mix}} = \sum f v_i \times MW_i \quad (1)$$

$$C_{p,\text{mix}} = \sum f v_i \times C_{p,i} \quad (2)$$

$$\text{LHV}_{\text{mix}} = \sum f v_i \times \text{LHV}_i \quad (3)$$

$$\text{HHV}_{\text{mix}} = \sum f v_i \times \text{HHV}_i \quad (4)$$

Equation (5) was used to calculate the Wobbe index.

$$W_0 = \frac{\text{HHV}}{\sqrt{SG}} \quad (5)$$

**Energy Analysis.** For the energy analysis, we apply first-law thermodynamic variables and key performance parameters from the Gas Machinery Research Council's *Guideline for Field Testing of Reciprocating Compressor Performance* [14].

*Air Compressor Thermal Efficiency.* The compressor's thermal efficiency can be determined using suction and discharge temperatures at a given compression ratio. TE<sub>AC</sub> quantifies the percentage difference between the actual and isentropic temperature changes across the compression process (Eq. (6)).

$$\text{TE}_{\text{AC}} = \frac{T_1 \left( \frac{k_{\text{AC}} - 1}{R_{\text{AC}} k_{\text{AC}}} - 1 \right)}{T_2 - T_1} \quad (6)$$

where  $R_{\text{AC}} = P_2/P_1$  and  $k_{\text{AC}} = C_{p,\text{avg}}/C_{v,\text{avg}}$ .

*Combustion Chamber Efficiency.* The combustion chamber's efficiency is the ratio of the energy absorbed by the substance working in the combustion chamber to the energy released by the

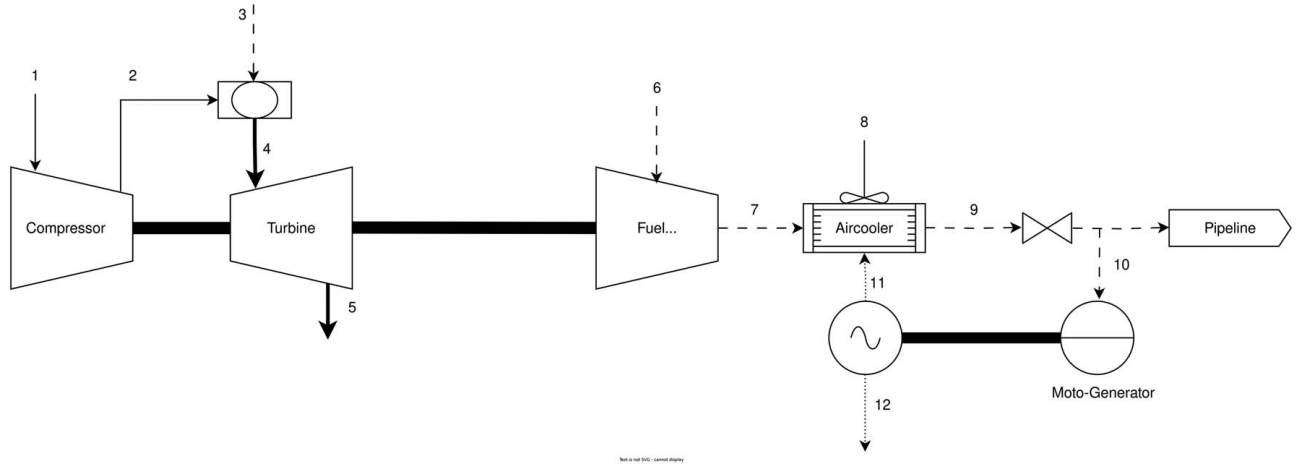


Fig. 1 Compressor station diagram

combustion of natural gas (Eq. (7)).

$$\epsilon_{CC} = \frac{\dot{m}_2 h_2 - \dot{m}_4 h_4}{\dot{m}_3 \text{LHV}} \quad (7)$$

**Gas Turbine Thermal Efficiency.** The turbine's thermal efficiency can be determined using exhaust gas inlet and discharge temperatures at a given pressure ratio.  $\text{TE}_{GT}$  represents the percentage difference between the actual temperature drop and the isentropic temperature drop across the turbine (Eq. (8)).

$$\text{TE}_{GT} = \frac{T_4 - T_5}{T_4 \left( 1 - \left( \frac{1}{R_{GT}} \right)^{\frac{k_{GT}-1}{k_{GT}}} \right)} \quad (8)$$

where  $R_{GT} = \frac{P_4}{P_5}$  and  $k_{GT} = \frac{C_{p,avg}}{C_{v,avg}}$ .

**Fuel Compressor Thermal Efficiency.** The thermal efficiency of the natural gas compressor can be determined using suction and discharge temperatures at a given compression ratio.  $\text{TE}_{FC}$  represents the percentage difference between the actual and isentropic temperature changes across the compressor (Eq. (9)).

$$\text{TE}_{FC} = \frac{T_6 \left( R_{FC}^{\frac{k_{FC}-1}{k_{FC}}} - 1 \right)}{T_7 - T_6} \quad (9)$$

where  $R_{FC} = \frac{P_7}{P_6}$  and  $k_{FC} = \frac{C_{p,avg}}{C_{v,avg}}$ .

**Heat Transfer Effectiveness of Air Coolers.** The heat transfer effectiveness of air coolers  $\epsilon_{AK}$  is obtained from the relationship between the energy transferred from the natural gas during cooling to meet Reglamento Único de Transporte de Gas Natural, para Colombia (Single Regulation for the Transportation of Natural Gas) RUT requirements and the maximum energy transferable by the working substance (Eq. (10)).

$$\epsilon_{AK} = \frac{(\dot{m}_7 h_7 - \dot{m}_9 h_9)}{\dot{m}_7 C_{p7} (T_7 - T_8)} \quad (10)$$

**EER of Air Coolers.** The energy efficiency ratio (EER) of the air cooler ( $\text{EER}_{AK}$ ) is defined as the ratio of the heat absorbed from the natural environment during cooling to meet RUT requirements to the electrical energy consumed by the air cooler fans (Eq. (11)).

$$\text{EER}_{AK} = \frac{(\dot{m}_7 h_7 - \dot{m}_9 h_9)}{\dot{W}_{11}} \quad (11)$$

**Fuel Consumption by Aero-Coolers.** The fuel consumption required to generate electrical energy for the air cooler fans is essential to lowering the natural gas temperature and meeting RUT requirements. According to the Gas Engine Generator Set G3508 data sheet, the specific fuel consumption is 7379 BTU/(hp h) (Eq. (12)).

$$\dot{m}_{10} = \text{SFC} \times \frac{\dot{W}_{11}}{3410 \times \text{LHV}} \quad (12)$$

**Electric Generator Efficiency.** The motor generator efficiency ( $\epsilon_{GE}$ ) is defined as the ratio of electrical energy consumed by the aero-coolers ( $\dot{W}_{11}$ ) to the thermal energy released from natural gas in the motor generator (Eq. (13)).

$$\epsilon_{GE} = \frac{\dot{W}_{11}}{\dot{m}_{10} \text{LHV}} \quad (13)$$

**Overall Efficiency of the Gas Compression System.** The overall efficiency of the gas compression system ( $\eta_{\text{total,CT}}$ ) is determined by the input energy and the energy used for driving the air and gas compressors (Eq. (14)).

$$\eta_{\text{CT,Thermal}} = \frac{(\dot{m}_7 h_7 - \dot{m}_6 h_6)}{\dot{m}_3 \text{LHV}} \quad (14)$$

**Compression Train Efficiency.** The compression train efficiency ( $\epsilon_{CT}$ ) is calculated as the ratio of energy used to compress natural gas to the net energy available from exhaust gas expansion, after subtracting the energy consumed by the air compressor (Eq. (15)).

$$\eta_{\text{CT}} = \frac{(\dot{m}_7 h_7 - \dot{m}_6 h_6)}{(\dot{m}_4 h_4 - \dot{m}_5 h_5) - (\dot{m}_2 h_2 - \dot{m}_1 h_1)} \quad (15)$$

**Turbine–Air Compressor Work Relationship (Back Work).** The gas turbine–air compressor work ratio expresses the ratio of compressor work to turbine work (Eq. (16)).

$$\text{BW} = \frac{\dot{W}_{AC}}{\dot{W}_{GT}} = \frac{\dot{m}_2 h_2 - \dot{m}_1 h_1}{\dot{m}_4 h_4 - \dot{m}_5 h_5} \quad (16)$$

**Ratio of Fuel Consumed to Processed Fuel.** The fuel consumption ratio ( $m^3$ ) represents the volume of natural gas consumed relative to the volume of compressed natural gas. It is calculated using Eq. (17).

$$\text{Ratio}_{\text{Fuel}} = \frac{\text{Volumen}_{FC}}{\text{Volumen}_{FP}} = \frac{(\dot{V}_{10} + \dot{V}_3)}{\dot{V}_6} \quad (17)$$

**System Efficiency.** System efficiency ( $\epsilon_{\text{sys}}$ ) quantifies the ratio of processed energy to consumed energy in the operation of the compression system (gas turbine and gas motor generator) (Eq. (18)).

$$\epsilon_{\text{sys}} = \frac{\text{Energy}_{\text{FP}}}{\text{Energy}_{\text{FC}}} = \frac{\dot{m}_6}{\dot{m}_{10} + \dot{m}_3} \quad (18)$$

**Fuel Transport Index.** The fuel transport index (FTI) represents the percentage of fuel consumed relative to the amount of gas compressed (Eq. (19)). A low FTI indicates a fuel-efficient compression unit.

$$\text{FTI}_{\text{TC}} = \frac{\dot{m}_{10} + \dot{m}_3}{\dot{m}_6} \times 100\% \quad (19)$$

**CO<sub>2</sub> Emission Index.** The CO<sub>2</sub> emission index ( $I_{\text{CO}_2}$ ) measures the tons of carbon dioxide produced per unit of fuel consumed in the compression system for processed fuel (Eq. (20)).

$$I_{\text{CO}_2} = \frac{\left(\frac{\text{NC} \times \text{MW}_C}{\text{NF} \times \text{MW}_F}\right) \times (\dot{m}_{10} + \dot{m}_3) \times (1 \text{ Ton}/1000 \text{ kg})}{\dot{V}_6 \times (1 \text{ Mm}^3/1,000,000)} \quad (20)$$

**Energy Cost Per Compressed Gas.** The energy cost per compressed gas is determined by evaluating the cost of fuel consumed relative to the amount of processed fuel (Eq. (21)).

$$C_{\text{FP}} = \frac{(\dot{V}_{10} + \dot{V}_3) \times \left(\frac{\text{\$USD}}{\text{m}^3}\right)}{\dot{V}_6 \times \left(\frac{1 \text{ Mm}^3}{1,000,000}\right)} \quad (21)$$

**Exergetic Analysis.** Exergy measures the maximum work potential of energy in a given state. It consists of two components: physical exergy and chemical exergy (Eq. (22)).

$$e_k = e_k^{\text{PH}} + e_k^{\text{CH}} \quad (22)$$

We calculate physical exergy using Eq. (23) for a pure substance and Eq. (24) for a gas mixture.

$$e_k^{\text{PH}} = h - h_0 - T_0(s - s_0) \quad (23)$$

$$e_k^{\text{PH}} = \frac{1}{M_k} \left( C_{P,k}(T - T_0) - T_0 \left[ C_{P,k} \ln\left(\frac{T}{T_0}\right) - R \ln\left(\frac{P}{P_0}\right) \right] \right) \quad (24)$$

$C_{P,k}$  comes from Eq. (25). The specific chemical exergy is calculated in Eq. (26), and  $e_k^{\text{CH}}$  is obtained from Eqs. (26) and (27) to fuel, when fuel was 100% H<sub>2</sub>,  $\lambda_F = 0.83$  [15,16].

$$C_{P,k} = \sum f_{v_i} C_{P,i} \quad (25)$$

$$e_k^{\text{CH}} = \frac{1}{M_k} \left( f_{v_i} e_i^{\text{CH}} + RT_0 \sum f_{v_i} \ln(f_{v_i}) \right) \quad (26)$$

$$\frac{e_k^{\text{CH}}}{\text{LHV}} = \lambda_F = 1.033 + 0.0169 \frac{x}{y} - \frac{0.0698}{x} \quad (27)$$

Equation (28) provides the exergy balance.  $\dot{E}_{F,k}$ ,  $\dot{E}_{P,k}$  and  $\dot{E}_{D,k}$  represent the exergy of fuel, product, and destruction, respectively:

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \quad (28)$$

Exergy efficiency is obtained from Eq. (29).

$$\epsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \times 100\% \quad (29)$$

**Exergoeconomic Analysis.** We apply the cost rate balance to each component of the study system, as expressed in Eq. (30) [17]:

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k \quad (30)$$

$\dot{Z}_k$  represents the investment cost rate, which includes equipment purchase costs (PEC<sub>k</sub>), and the operation and maintenance cost rate ( $\varphi$ ).

We calculate the cost rate balance components using Eqs. (31)–(33) [17], applying the cost-levelization approach. Table 7 presents key parameters for the exergoeconomic analysis, while Table 8 provides formulas for calculating the compressor station's PEC.

$$\dot{C}_{P,k} = c_{P,k} \dot{E}_P \quad (31)$$

$$\dot{C}_{F,k} = c_{F,k} \dot{E}_F \quad (32)$$

$$\dot{Z}_k = \frac{\text{PEC}_k \left[ \frac{i_r(1+i_r)^{n_y}}{(1+i_r)^{n_y} - 1} \right] \varphi}{3600(\text{RTY})} \quad (33)$$

We calculated the costs of destroyed exergy using Eq. (34), assuming fixed product prices [17].

$$\dot{C}_D = c_{F,k} \dot{E}_{D,k} \quad (34)$$

## Results and Discussion

This study examines the impact of using natural gas–hydrogen blends as fuel in a compression station powered by a gas turbine. The analysis evaluates the energy, exergy, and exergoeconomic effects of this process.

**Properties of Fuel Mixture Results.** Table 1 presents the volumetric composition of the natural gas used in this study. Table 2 presents the results of the analysis of natural gas–hydrogen fuel mixtures. The analyzed properties include molecular weight, specific heat at constant pressure, lower heating value, higher heating value, and the Wobbe index. The energy content per unit mass increases 50% of its original value for H<sub>2</sub> concentrations above 76% but increases by 38.6% when transitioning from 90% to 100% hydrogen. Meanwhile, energy content per unit volume decreases by 32%, and  $C_p$  rises 6.5 times from 0% to 100% hydrogen. Despite these changes, the Wobbe index remains within the classification limits of natural gas for all studied hydrogen proportions [18].

**Thermodynamic Model and Energy Analysis Results.** The thermodynamic model is based on the thermal efficiencies of its components, calculated using Eqs. (6)–(13). Table 3 presents the values applied in the model. Additionally, we incorporate the combustion model proposed by Barreto et al. [19]. We simulate the different fuel mixtures under the same processed energy conditions for

**Table 1 Volumetric composition of refinery gas**

Compound	Volume fraction (%)
CH <sub>4</sub>	98.83
C <sub>2</sub> H <sub>6</sub>	0.23
C <sub>3</sub> H <sub>8</sub>	0.05
C <sub>4</sub> H <sub>10</sub>	0.04
C <sub>5</sub> H <sub>12</sub>	0.01
C <sub>6</sub> H <sub>14</sub>	0.02
CO <sub>2</sub>	0.16
N <sub>2</sub>	0.67

**Table 2 Properties of the natural gas and hydrogen fuel mixture**

H <sub>2</sub> (%)	MW (kg/kmol)	C <sub>p</sub> (kJ/kg °C)	LHV (kJ/kg)	LHV (kJ/kg) ratio to 0% H <sub>2</sub>	HHV (kJ/m <sup>3</sup> )	LHV (kJ/m <sup>3</sup> ) ratio to 0% H <sub>2</sub>	Wo (kJ/m <sup>3</sup> )
0	16.4	2.18	49,204	1.00	37,322	100.0	47,831
10	14.9	2.34	50,166	1.02	34,792	93.2	45,877
20	13.5	2.54	51,332	1.04	32,263	86.4	43,836
30	12.1	2.79	52,776	1.07	29,733	79.7	41,696
40	10.6	3.10	54,609	1.11	27,203	72.9	39,443
50	9.2	3.52	57,013	1.16	24,674	66.1	37,057
60	7.8	4.08	60,305	1.23	22,144	59.3	34,512
70	6.3	4.89	65,088	1.32	19,614	52.6	31,773
80	4.9	6.19	72,670	1.48	17,085	45.8	28,796
90	3.5	8.56	86,527	1.76	14,555	39.0	25,526
100	2.0	14.27	119,946	2.44	12,026	32.2	21,965

**Table 3 Parameter and model values**

Air compressor efficiency (%)	88
Air compressor pressure ratio	10.7s
Gas turbine efficiency (%)	90
Gas turbine pressure ratio	10
AFR	60
$f_{v_{iO_2}}$ (%)	14.13
Fuel compressor efficiency (%)	38
Air compressor pressure ratio	1.3
Heat transfer effectiveness air cooler (%)	82
EER (kW/kW)	12.97
SFC (kW/kW)	2.9
Natural gas flow (m <sup>3</sup> /dia)	168,485

an average day at the compressor station, which manages 168,485 cubic meters of natural gas per day.

Table 4 presents the energy analysis results, including mass flows of air, fuel consumed, processed fuel, fuel for the motor generator,

combustion temperature, exhaust gas outlet temperature, processed fuel outlet temperature, heat, and air cooler work.

Our analysis reveals that switching from 100% natural gas to 100% hydrogen reduces air mass flow by 19.3% and fuel consumption (both consumed and processed) by 61.5%. The fuel mass flow for the motor generator increases by 2.6%, while combustion and exhaust gas outlet temperatures drop to 855 °C and 411 °C, respectively. The processed fuel outlet temperature reaches 47 °C, and the heat and air cooler work increases by 208%.

Table 5 presents the effects of different fuel mixtures on combustion efficiency, compressor train efficiency, compressor train thermal efficiency, downstream work, fuel consumption ratio, system efficiency, fuel transport rate, CO<sub>2</sub> emission rate, and energy cost per compressed gas.

Switching from 100% natural gas to 100% hydrogen reduces combustion efficiency by 30%. The efficiency of the compression train and the overall gas compression system reach 29.8% and 6.5%, respectively. Back work increases by 9.6%, while the fuel consumption ratio and fuel transport index rise by 9.6%. System efficiency decreases by 8.7%.

**Table 4 Energy analysis of compressor station with fuel mixture**

NG (%)	H <sub>2</sub> (%)	$\dot{m}_1$ (kg/s)	$\dot{m}_2$ (kg/s)	$\dot{m}_6$ (kg/s)	$m_{10}$ (kg/s)	T <sub>4</sub> (°C)	T <sub>5</sub> (°C)	T <sub>9</sub> (°C)	Q <sub>AK</sub> (kW)	W <sub>AK</sub> (kW)
100	0	9.71	0.162	1.337	0.0099	987	500	45	135	121
90	10	9.65	0.158	1.309	0.0102	983	497	45	144	130
80	20	9.57	0.154	1.276	0.0105	979	494	45	155	140
70	30	9.48	0.150	1.237	0.0109	974	491	45	169	151
60	40	9.38	0.144	1.192	0.0113	967	486	45	184	165
50	50	9.25	0.138	1.137	0.0116	960	481	46	203	182
40	60	9.10	0.129	1.069	0.0120	950	475	46	226	203
30	70	8.90	0.119	0.984	0.0123	937	466	46	255	229
20	80	8.65	0.106	0.874	0.0123	920	454	47	292	262
10	90	8.31	0.088	0.726	0.0119	895	437	47	343	308

**Table 5 Operation indicators of compressor station with fuel mixture**

NG (%)	H <sub>2</sub> (%)	$\eta_{Comb}$ (%)	$\eta_{CT}$ (%)	$\eta_{CT,Therma}$ (%)	BW (%)	Ratio <sub>Fuel</sub> (m <sup>3</sup> <sub>FC</sub> /m <sup>3</sup> <sub>FP</sub> )	$\epsilon_{Sys}$ (kW <sub>FC</sub> /kW <sub>FP</sub> )	FTI <sub>TC</sub> (%)	I <sub>CO<sub>2</sub></sub> (Ton CO <sub>2</sub> /Mm <sup>3</sup> <sub>FP</sub> )	C <sub>FP</sub> (\$USD/Mm <sup>3</sup> <sub>FP</sub> )
100	0	95.4	6.1	1.9	56.1	0.128	7.79	12.84	64.3	72,579
90	10	94.5	6.7	2.1	56.2	0.129	7.77	12.88	58.0	69,514
80	20	93.4	7.3	2.3	56.3	0.129	7.74	12.93	51.8	66,420
70	30	92.1	8.1	2.5	56.5	0.130	7.70	12.98	45.5	63,283
60	40	90.6	9.0	2.7	56.8	0.130	7.67	13.04	39.2	60,083
50	50	88.8	10.2	3.0	57.0	0.131	7.62	13.12	32.9	56,787
40	60	86.5	11.8	3.3	57.4	0.132	7.56	13.22	26.5	53,332
30	70	83.6	13.8	3.8	57.9	0.134	7.49	13.35	20.1	49,596
20	80	79.8	16.8	4.4	58.6	0.135	7.40	13.51	13.5	45,299
10	90	74.5	21.5	5.2	59.7	0.137	7.28	13.74	6.9	39,663
0	100	66.8	29.8	6.5	61.4	7.109	14.07	0.14	0.0	29,590

**Table 6 Definition of fuel, product exergy, and cost rate balance of compressor station**

Equipment	$\dot{E}_F$	$\dot{E}_P$	Cost rate balance and auxiliary equation
AC	$\dot{E}_{W_{AC}}$	$\dot{E}_2 - \dot{E}_1$	$\dot{C}_2 - \dot{C}_1 = \dot{C}_{W_{AC}} + \dot{Z}_{AC}$ $c_1 = 0$
CC	$\dot{E}_3$	$\dot{E}_4 - \dot{E}_2$	$\dot{C}_4 - \dot{C}_2 = \dot{C}_3 + \dot{Z}_{CC}$
GT	$\dot{E}_4 - \dot{E}_5$	$\dot{E}_{W_{GT}}$	$\dot{C}_{W_{GT}} = \dot{C}_4 - \dot{C}_5 + \dot{Z}_{GT}$ $c_5 = c_4$
FC	$\dot{E}_{W_{FC}}$	$\dot{E}_7 - \dot{E}_6$	$\dot{C}_7 - \dot{C}_6 = \dot{C}_{W_{FC}} + \dot{Z}_{FC}$
AK	$\dot{E}_8 + \dot{E}_{11}$	$\dot{E}_7 - \dot{E}_9$	$\dot{C}_7 - \dot{C}_9 = \dot{C}_8 + \dot{C}_{11} + \dot{Z}_{AK}$ $c_8 = 0$
MGEN	$\dot{E}_{10}$	$\dot{E}_{11} + \dot{E}_{12}$	$\dot{C}_{11} + \dot{C}_{12} = \dot{C}_{10} + \dot{Z}_{MGEN}$

**Table 7 Exergy analysis of compressor station with fuel mixture**

NG (%)	H <sub>2</sub> (%)	e <sub>3</sub> (kJ/kg)	ED <sub>CC</sub> (kW)	ε <sub>CC</sub> (%)	ED <sub>FC</sub> (kW)	ε <sub>FC</sub> (%)	ED <sub>AK</sub> (kW)	ε <sub>AK</sub> (%)	ED <sub>MGen</sub> (kW)	ε <sub>MGen</sub> (%)	ED <sub>Tota</sub> (kW)	ε <sub>Tot</sub> (%)
100	0	51,358	2379	71.4	79	48.8	99	18.6	339	33.1	3691	0.6
90	10	52,274	2391	71.1	85	48.9	106	18.7	356	33.1	3727	0.6
80	20	53,383	2367	71.3	91	49.0	114	18.9	375	33.2	3734	0.7
70	30	54,757	2340	71.5	99	49.1	123	19.1	398	33.3	3742	0.8
60	40	56,507	2308	71.7	108	49.2	134	19.2	424	33.3	3752	0.8
50	50	58,809	2271	71.9	119	49.3	148	19.4	455	33.5	3765	0.9
40	60	61,973	2226	72.2	132	49.4	164	19.6	494	33.6	3782	1.0
30	70	66,587	2170	72.6	149	49.5	184	19.8	541	33.7	3804	1.1
20	80	73,929	2101	73.1	171	49.6	211	20.0	602	33.9	3833	1.3
10	90	87,401	2009	73.8	200	49.7	247	20.2	683	34.2	3874	1.6
0	100	120,090	1883	74.8	242	49.8	297	20.4	797	34.5	3935	1.9

**Table 8 Parameter for exergoeconomic analysis**

Item	Value
RTY (h)	7446
φ	1.06
n <sub>y</sub> (years)	20
i <sub>r</sub> (%)	15%

When the hydrogen content increases from 0% to 50%, the CO<sub>2</sub> emission rate drops by 49%, and the energy cost per unit volume decreases by 21.8%.

**Exergy Analysis.** The exergy analysis examines the effects of hydrogen–natural gas mixtures on the combustion chamber, fuel compressor, air cooler, motor generator, and total system. Table 6 defines the fuel and exergy product of each compression station

**Table 9 Formulas for calculating the PEC of plant components**

Component	Purchased equipment costing functions
AC	$PEC_{AC} = \frac{71.1m_{Air}}{0.9 - \eta_{AC}} \left( \frac{P_{out}}{P_{in}} \right) \ln \left( \frac{P_{out}}{P_{in}} \right)$ [20]
CC	$PEC_{CC} = \left( \frac{46.08m_{gases}}{0.995 - \frac{P_i}{P_e}} \right) (1 + e^{(0.0187t_e - 26.4)})$ [20]
GT	$PEC_{GT} = \frac{49.34m_{gases}}{0.92 - \eta_{GT}} \ln \left( \frac{P_{in}}{P_{out}} \right) (1 + e^{(0.0367t_m - 54.4)})$ [20]
FC	$PEC_{FC} = \frac{71.1m_{fuel}}{0.9 - \eta_{FC}} \left( \frac{P_{out}}{P_{in}} \right) \ln \left( \frac{P_{out}}{P_{in}} \right)$ [20]
AK	$PEC_{AK} = 30A_{AK}^{0.4}$ [21]
MGEN	$PEC_{Gen} = 695.04\dot{W}_{elect}$ [22]

**Table 10 Exergoeconomic analysis of compressor station with fuel mixture**

NG (%)	H <sub>2</sub> (%)	C <sub>3</sub> (USD/GJ)	C <sub>3</sub> (USD/GJ) ratio to 0% H <sub>2</sub>	C <sub>9</sub> (USD/GJ)	C <sub>3</sub> (USD/GJ) ratio to 0% H <sub>2</sub>	C <sub>D,Total</sub> (\$/h)	C <sub>D,Total</sub> (\$/h) ratio to 0% H <sub>2</sub>
100	0	16.23	1.00	16.3	1.00	249.6	1.00
90	10	16.69	1.03	16.77	1.03	259.1	1.04
80	20	17.21	1.06	17.3	1.06	267.4	1.07
70	30	17.81	1.10	17.91	1.10	277.1	1.11
60	40	18.5	1.14	18.61	1.14	288.4	1.16
50	50	19.31	1.19	19.43	1.19	301.5	1.21
40	60	20.23	1.25	20.37	1.25	316.9	1.27
30	70	21.27	1.31	21.44	1.32	334.6	1.34
20	80	22.35	1.38	22.54	1.38	353.6	1.42
10	90	23.02	1.42	23.25	1.43	367.3	1.47
0	100	20.82	1.28	21.07	1.29	337.1	1.35

**Table 11 Relative cost difference by component**

GN (%)	H <sub>2</sub> (%)	AC	CC	GT	FC	AK	MGEN
100	0	16.8	139.1	59.7	8.4	5.8	19.8
90	10	17.2	143.7	61.1	9.3	6.4	21.4
80	20	17.6	146.7	62.6	10.2	7.1	23.3
70	30	18.0	150.1	64.2	11.4	7.9	25.5
60	40	18.4	153.8	66.1	12.9	9.0	28.2
50	50	18.9	157.8	68.2	14.7	10.3	31.6
40	60	19.4	162.1	70.5	17.1	12.0	36.0
30	70	19.9	166.2	72.9	20.1	14.2	41.5
20	80	20.2	169.0	75.0	23.9	17.0	48.5
10	90	19.9	166.5	75.2	28.6	20.5	56.6
0	100	17.1	141.1	65.8	31.0	22.4	59.7

equipment. Table 7 presents the specific exergy of the fuel mixture, exergy destruction, and exergy efficiency.

With a fuel mixture containing up to 90% hydrogen, the specific exergy increases by 23%, while at 100% hydrogen, it rises by 136.2%, driven by the chemical exergy calculated in Eq. (27). Exergy destruction in the combustion chamber decreases by 8% for mixtures up to 60% hydrogen but decreases by 20.8% for mixtures up to 100% hydrogen, compared to 100% natural gas. The exergy efficiency of the combustion chamber is 71.4% with pure natural gas and up to 74.8% with pure hydrogen.

Switching from 100% natural gas to 100% hydrogen increases exergy destruction in the fuel compressor, air cooler, and motor generator by 206.8%, 199.2%, and 134.9%, respectively. Their exergy efficiencies reach values of 49.8%, 20.4%, and 34.5%. Exergy destruction in the station compressor increases by 6.6% for mixtures up to 100% hydrogen. The exergy efficiency of the station compressor reaches 1.9% with pure hydrogen.

**Exergoeconomic Analysis.** The exergoeconomic analysis examines the impact of hydrogen–natural gas mixtures on compressors, the combustion chamber, the gas turbine, and the Heat Recovery Steam Generator (HRSG). Table 6 shows the cost rate balance for each compression station equipment. Table 8 presents key parameters for exergoeconomic analysis, while Table 9 provides the formulas for calculating the PEC of the compressor station.

Table 10 presents the specific fuel exergy cost, the specific exergy cost of processed fuel, and the exergy destruction cost rate for the compressor station under each fuel mixture. With up to 50% hydrogen, the specific fuel exergy cost and the specific exergy cost of processed fuel increase by 20%, while at 100% hydrogen, the increase reaches 30% respect to 100% hydrogen. The exergy destruction cost rises by 4.8% on average for every 10% increase in hydrogen blended in the fuel.

Table 11 presents the exergy destruction cost rate of the gas station. With 100% hydrogen, while the gas turbine components increase the exergy destruction cost rate by less than 25%, the remaining components show increases of more than 200%.

## Conclusion

Using natural gas–hydrogen mixtures as fuel advances decarbonization by reducing CO<sub>2</sub> emissions as the hydrogen fraction increases. The analysis of energetic, exergetic, and exergoeconomic variables in the compressor station reveals the following trends with higher hydrogen content in the fuel mixture: (1) the calorific value of the fuel mixture increases, reducing the required mass flow of fuel and air to process the same amount of energy in the compressor station. (2) The Wobbe index decreases but remains within the classification limits of natural gas for all studied hydrogen proportions. (3) Fuel exergy increases by 12% with 50% hydrogen and by a factor of 2.36 with 100% hydrogen. (4) Exergy destruction decreases in the air compressor, combustion chamber, and gas

turbine due to lower fuel and air mass flow, while it increases in the fuel compressor, air cooler, and motor generator due to changes in the specific exergy of the fuel mixture. (5) The specific exergy costs of fuel, processed fuel, and the exergy destruction cost rate increase, making fuel processing more expensive as hydrogen content rises.

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## Conflict of Interest

There are no conflicts of interest.

## Data Availability Statement

The authors attest that all data for this study are included in the article.

## Nomenclature

$e$	= Specific cost (USD/kJ)
$e$	= Specific exergy (kJ/kg)
$h$	= Specific enthalpy (kJ/kg)
$k$	= Specific heat ratio
$P$	= Pressure (kPa)
$R$	= Specific gas constant
$T$	= Temperature (°C)
$\dot{m}$	= Mass flow rate (kg/s)
$\dot{Q}$	= Heat transfer (kW)
$\dot{V}$	= Volume flow rate (m <sup>3</sup> /s)
$\dot{W}$	= Electric power (kW)
$C_p$	= Specific heat at constant pressure (kJ/kg °C)
$C_v$	= Specific heat at constant volume (kJ/kg °C)
HHV	= Higher heating value (kJ/kg)
LHV	= Lower heating value (kJ/kg)

## Greek Symbols

$\alpha$	= Air stoichiometry ratio
$\lambda$	= Excess air ratio
$\varepsilon$	= Exergetic efficiency, (%)

## Abbreviations

AC	= Air compressor
AK	= Air cooler
BW	= Gas turbine–air compressor work ratio
CC	= Combustion chamber
CT	= Compression train
FC	= Fuel compressor
FC	= Fuel consumed
FP	= Process fuel
FTI	= Fuel transport index
GE	= Motor generator
GT	= Gas turbine
Mm <sup>3</sup>	= Mega cubic meter
MPC	= Million cubic feet
NC	= Moles of carbon
NF	= Moles of fuel
SFC	= Specific fuel consumption
Sys	= System
TE	= Thermal efficiency

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