Experimental impact of exhaust gas recirculation and hydrogen injection on the emissions of a micro gas turbine

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Abstract. To achieve a zero-carbon economy with gas turbines, amine-based carbon capture has emerged as a potential solution, though it comes with a significant energy cost. Exhaust gas recirculation (EGR) is therefore used to mitigate the efficiency penalty associated with carbon capture by increasing the CO_2 concentration in exhaust gases and reducing the overall gas mass flow. However, operating near stoichiometric combustion conditions elevates CO emissions, thereby limiting the feasible EGR rate. Hydrogen cofiring has been proposed as a promising approach to stabilize combustion under these conditions, where the air-fuel ratio approaches unity. Despite its potential, the impact of hydrogen cofiring on performance and emissions remains largely unexplored. To address this gap, experiments are carried out using a 3 kW_e micro gas turbine (MTT EnerTwin ®) fuelled with methane blend containing 20% hydrogen. This study examines the effects on emissions, including CO_2, O_2, NO_x and CO. The modified setup, which supports higher EGR rates, provides valuable insights into how hydrogen cofiring can stabilize combustion and enhance carbon capture efficiency. These findings are crucial for scaling the behaviour of micro gas turbines to industrial applications and assessing the combined potentials of EGR and hydrogen to minimize the energy penalty of carbon capture technologies.

Nomenclature

α	air-to-fuel molar ratio
α_0	air-to-fuel molar ratio at no EGR
CAPEX	capital expenditure
CCGT	combined cycle gas turbine
ϵ	absolute uncertainty
EGR	exhaust gas recirculation
GT	gas turbine
λ	air-fuel equivalence ratio
mGT	micro gas turbine
MM_f	molar mass of the fuel
MM_o	molar mass of the oxidizer
NO_x	nitrogen oxides
PCC	post combustion carbon capture
x	number of carbon in the fuel
y	number of hydrogen in the fuel

Introduction

Gas turbines are increasingly recognized as essential components of the future energy mix. Their inherent operational flexibility makes them well-suited to compensate for the intermittency associated with renewable energy sources. However, a major limitation remains their emission of carbon dioxide, which must be mitigated to align with decarbonization targets. Among the available options, amine-based post-combustion carbon capture (PCC) stands out as the most mature and commercially viable technology for reducing CO_2 emissions from gas turbines.

To address the energy penalty associated with PCC, exhaust gas recirculation (EGR) has emerged as a promising complementary strategy. EGR provides several benefits:

1. increases the CO_2 concentration in the exhaust gas;
2. reduces the total mass flow to be processed by the capture unit;
3. decreases the O_2 concentration, limiting oxidative degradation of the amines;
4. lowers NO_x emissions, thereby reducing acid-related degradation of the solvents.

Maximizing the EGR level has thus been identified as a profitable strategy to reduce both the energy penalty and the capital expenditure (CAPEX) associated with post-combustion carbon capture, as demonstrated by Verhaeghe et al. [1]. However, El Kady et al. [2] have highlighted a significant drawback: as combustion conditions approach stoichiometry, the risk of carbon monoxide emissions increases. In their recent work, authors of this paper [3] experimentally investigated the application of EGR on a micro gas turbine up to the point of flameout. Their results confirmed the exponential rise in CO emissions associated with high EGR levels. Although EGR effectively increases the dry

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molar CO_2 concentration (up to 8%) and reduces NO_x and O_2 emissions, the resulting CO levels become unacceptably high, compromising the environmental viability of the system.

Hydrogen can provide a valuable solution by reducing the carbon content of the fuel and improving combustion stability. Schefer et al. [4] investigated hydrogen enrichment and demonstrated that it leads to an increased concentration of OH• radicals, which promote the oxidation of carbon monoxide ($CO \rightarrow CO_2$). Similarly, du Toit et al. [5] found that H_2 introduces additional H•, O•, and OH• radicals during combustion enhancing the complete oxidation of CO to CO_2.

However, the issue of NO_x emissions remains a concern in the context of H_2 co-combustion. Jamshidiha et al. [6] observed that hydrogen addition can increase flame temperature, thereby accelerating thermal NO_x formation in the combustion chamber. The impact of small hydrogen fractions on NO_x production—and its potential to damage the chemical stability of amine-based solvents, as suggested by Fostaas et al. [7]—has not yet been fully characterized.

The experimental setup presented in this paper aims to address this gap by investigating how hydrogen co-firing can extend the feasible EGR levels in gas turbines. A 3 kW_e micro gas turbine is operated with both pure methane and a 20% vol. H_2 blend. Emissions of CO, CO_2, O_2, NO, and NO_2 are measured across a range of EGR levels. The primary objectives are to assess the potential increase in NO_x emissions and to better quantify the extent to which hydrogen reduces CO emissions under high EGR conditions.

1 Methodology

1.1 Analytical prediction

Recirculating the exhaust gases to the compressor inlet reduces the fresh air intake and shifts the combustion conditions closer to stoichiometric. According to chemical equilibrium, a theoretical maximum in CO_2 concentration is achieved at stoichiometry. For a generic hydrocarbon fuel of the form C_xH_y, the corresponding maximum wet and dry molar CO_2 concentrations can be expressed as shown in Equation 1 and Equation 2, respectively:

$$wet\ CO_{2\,max} = \frac{x}{4.76x + 1.44y} \quad (1)$$

$$dry\ CO_{2\,max} = \frac{x}{4.76x + 0.94y} \quad (2)$$

While EGR aims to increase the CO_2 content in the exhaust, introducing hydrogen into the fuel blend decreases the theoretical maximum CO_2 concentration, since H_2 does not contain any carbon atoms. For methane (CH_4), the theoretical maximum concentrations are approximately 11.7% (dry) and 9.5% (wet). These values asymptotically approach zero as the hydrogen fraction increases to 100%. However, as shown in Figure 1, up to 20% (vol.) hydrogen can be added to the methane blend before a relative reduction greater than 5% in the maximum theoretical CO_2 concentration is observed.

In its technical report on hydrogen retrofit for gas turbines [8], ETN Global defined three hydrogen co-firing ranges, each associated with specific retrofit implications:

- Low-level co-firing (0–10% vol.): no retrofit required;
- Medium-level co-firing (10–30% vol.): minor modifications, generally not significant;
- High-level co-firing (30–100% vol.): substantial retrofit requirements.

Therefore, a 20% (vol.) hydrogen blend lies within the medium co-firing range, requiring no major modifications. It also preserves a sufficiently high CO_2 concentration for effective carbon capture, while simultaneously improving flame stability and reducing CO emissions, as previously reported by Schefer [4] and du Toit [9]. In this work, various EGR levels are applied to a modified micro gas turbine (MTT EnerTwin ®), and emissions are compared for both pure methane and a methane-hydrogen (20% vol.) blend.

1.2 Experimental Setup

As experimental validation at the industrial scale is impractical, a 3 kW_e micro gas turbine (MTT EnerTwin ®) is employed. The system is equipped with an external EGR loop to allow for adjustable recirculation rates. Several modifications were made to enhance experimental flexibility, including the addition of external control valves (13–14), a back-pressure valve (16–17), and an electric preheater at the compressor inlet (2–3). The system configuration is illustrated in Figure 2.

Fresh ambient air enters the system (1), is preheated (2–3), and compressed to approximately 2.7 bar (4-5). Fuel is injected in the combustion chamber (6), and the high-temperature gas expands through the turbine (7–8), generating power. Residual heat is recovered in the internal recuperator (8-9), which preheats the incoming air stream—a common feature in micro gas turbines, though absent in most industrial-scale units. The efficiency is further increased via an external economizer (9–10), used for domestic hot water production.

Exhaust gases are optionally recirculated prior to release at the stack (17). The originally integrated EGR valve (11–12) was decoupled from the turbine controller to allow manual operation. Since the internal recirculation loop proved insufficient to achieve high EGR rates, an external loop (13–14) was added. A back-pressure valve (16–17) was also installed to promote recirculation in the absence of a dedicated fan.

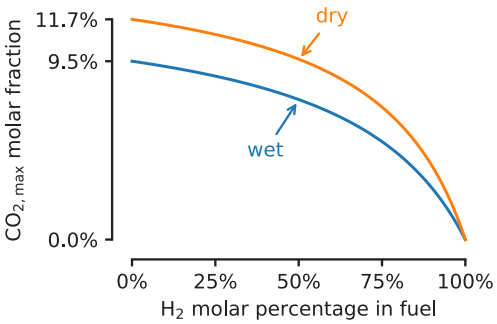

Fig. 1. Theoretical dry CO_2 molar concentration as a function of hydrogen fraction in a CH_4–H_2 blend at stoichiometric conditions.

1.3 Fuel Blends and Instrumentation

Two high-purity gas cylinders are used for testing, following the initial system preheating with natural gas. The first cylinder contains pure methane (quality 2.5, i.e., 99.5%). The second contains a 20% vol. hydrogen blend (±2% rel.) with methane (H_2 quality 5.0, i.e., 99.999%; CH_4 quality 2.5, i.e., 99.5%).

System pressures are monitored at various locations using Huba Control ® pressure transmitters. Temperatures are measured using either K-type thermocouples (Omega ®) or NTC sensors (Tasseron ®), depending on the application. Exhaust gas composition is analyzed at the stack (17) using a Testo 350 ® gas analyser. The measurement accuracy of the device is summarised in Table 1.

Table 1. Accuracy ranges of the Testo 350 ® gas analyser (r.v.: read value).

	Accuracy	Range
O_2	±0.2% r.v.	full scale
CO	±10 ppm ±5% r.v. ±10% r.v.	<199 pm 200-2000 ppm >2000 ppm
NO	±5 ppm ±5% r.v. ±10% r.v.	<99 pm 100-1999.9 ppm >2000 ppm
NO_2	±2 ppm ±5% r.v.	<39.9 pm >40 ppm
CO_2	±0.3% ±1% r.v ±0.5% r.v. ±1.5% r.v	0-25% >25%

1.4 Test Protocol

Each test campaign begins with a 2-hour preheating phase using natural gas to reach steady-state conditions. The turbine operates at 70% nominal load (i.e., 2.2 kW_e on the 3.2 kW_e at nominal load), and the compressor inlet temperature is maintained at 25°C using the electric heater. Once stable, the fuel supply is switched to either pure methane or the H_2–CH_4 blend. Only one gas cylinder is connected at a time, and EGR levels are varied sequentially. Due to small increments between EGR steps, system stabilization requires less than 5 minutes, followed by up to 10 minutes of data acquisition per operating point.

In case of flameout or grid-related electrical instabilities, the turbine is shut down and a subsequent 20-minute natural gas preheating phase is performed to re-establish steady-state conditions before resuming testing.

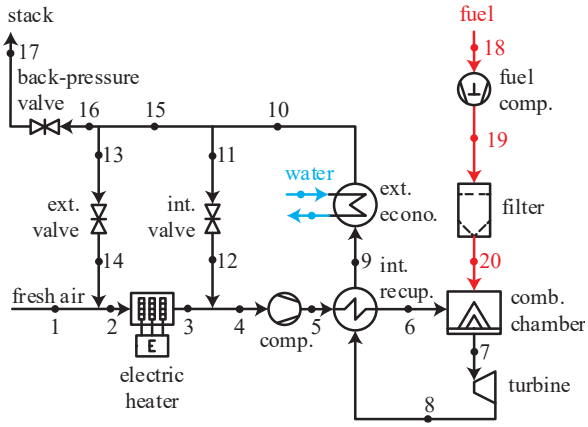

Fig. 2. Schematic of the modified MTT EnerTwin ® micro gas turbine, equipped with an extended EGR loop, back-pressure valve, and external fuel blend injection system.

1.5 Definition of the EGR level

The amount of EGR is defined as the mass fraction of the exhaust gases being recirculated back to the compressor inlet without any drying process. Since the set-up is not equipped with flow meters inside the recirculation loop, the exhaust gas recirculation (EGR) ratio is computed from the measured oxygen concentration in the exhaust gases ($O_{2\,dry}$). Based on the generic combustion equation (Equation 3) and the assumption of constant turbine mass flow (Equation 4) the EGR expression (Equation 5) depends only on the fuel composition (x, y) and the dry molar oxygen fractions in the exhaust gases ($O_{2\,dry}$), in ambient air ($O_{2\,dry\,air}$), and in the exhaust without EGR ($O_{2\,dry\,0}$).

Because $O_{2\,dry}$ is much larger than CO_2 in the exhaust, the molar air-fuel ratios with EGR (Equation 10) and without EGR (Equation 11) are computed from the oxygen fraction, thereby reducing the relative uncertainty. The fuel composition (Equations 6-7) and the air composition (Equations 8-9) allow the molar masses of fuel (Equation 12) and oxidiser (Equation 13) to be derived.

Finally, the absolute uncertainty on the EGR level is expressed by propagating the uncertainties on the oxygen molar fractions, air composition, and fuel blend components (CH_4, H_2) in Equation 14.

$$C_xH_y + \alpha(\beta O_2 + \gamma N_2) \rightarrow x\,CO_2 + \frac{y}{2}H_2O + \left(\alpha\beta - x - \frac{y}{4}\right)O_2 + \alpha\gamma N_2 \quad (3)$$

$$MM_f + \alpha_0 MM_o = \frac{\alpha MM_o + MM_f}{1 - EGR} \quad (4)$$

$$EGR = 1 - \frac{\alpha MM_o + MM_f}{\alpha_0 MM_o + MM_f} \quad (5)$$

$$x = \%CH_4 \quad (6)$$

$$y = \%H_2 \quad (7)$$

$$\beta = \%O_{2\ dry\ air} \quad (8)$$

$$\gamma = 1 - \%O_{2\ dry\ air} \quad (9)$$

$$\alpha = -\frac{x + \frac{y}{4}}{(\beta + \gamma)\,\%O_{2\ dry} - \beta} \quad (10)$$

$$\alpha_0 = -\frac{x + \frac{y}{4}}{(\beta + \gamma)\,\%O_{2\ dry\ 0} - \beta} \quad (11)$$

$$MM_f = 12\%\,CH_4 + 2\%\,H_2 \quad (12)$$

$$MM_o = 28 + 4\,\%O_{2\ dry\ air} \quad (13)$$

$$\epsilon_{EGR} = \left|\frac{\partial EGR}{\partial\,\%O_{2\ dry}}\right| \epsilon_{\%O_{2\ dry}} + \left|\frac{\partial EGR}{\partial\,\%O_{2\ dry\ air}}\right| \epsilon_{\%O_{2\ dry\ air}} + \left|\frac{\partial EGR}{\partial\,\%O_{2\ dry\ 0}}\right| \epsilon_{\%O_{2\ dry\ 0}} + \left|\frac{\partial EGR}{\partial\,\%CH_4}\right| \epsilon_{\%CH_4} + \left|\frac{\partial EGR}{\partial\,\%H_2}\right| \epsilon_{\%H_2} \quad (14)$$

Due to the asymptotic behaviour of $O_{2\ dry\ 0}$ with the EGR rate (Figure 3), this method yields large uncertainties at low EGR. In this region the analytical oxygen curve is nearly flat, so even small fluctuations in $O_{2\ dry}$ lead to large inaccuracies in EGR. Nevertheless, for low oxygen concentrations (~10%), the uncertainty (ϵ_{EGR}) remains within 3.6% abs.

2 Results and Discussion

2.1 O_2 and CO_2 Content

As shown in Figure 3, the measured dry molar concentration of O_2 across different EGR levels (blue markers) closely follows the theoretical prediction for methane combustion (blue curve). Without EGR, the dry O_2 concentration reaches approximately 18.9%, which is consistent with the high dilution typical of micro gas turbines, where the air–fuel equivalence ratio λ is around 9. In contrast, industrial-scale gas turbines generally operate at lower λ to increase the turbine inlet temperature and, consequently, the Carnot efficiency. In this experiment, the dry O_2 concentration decreases to a minimum of 9.7% before flameout is observed.

The lower section of Figure 3 presents the absolute deviation in O_2 concentration relative to the analytical baseline for methane. This format highlights the small but growing difference caused by hydrogen enrichment in the blend. As hydrogen requires significantly less oxygen to combust than methane, the residual O_2 in the exhaust is higher when hydrogen is present. The respective stoichiometric reactions are provided in Equations 15 and 16.

$$H_2 + 0.5O_2 \rightarrow H_2O \quad (15)$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (16)$$

Notably, the hydrogen-enriched fuel allows the EGR rate to be increased from 80% to 84%. While this may appear marginal, the asymptotic nature of the CO_2 concentration curve magnifies its effect. As shown in Figure 4, EGR application with pure methane increases dry CO_2 concentration from 1.2% to 6.5%. With the hydrogen blend, CO_2 concentration further rises to 7.8% at 84% EGR. The difference between the experimental points (orange dots) and the analytical prediction (orange line) comes from both the error of the gas analyser as well as from the uncertainty associated to the blend composition. Although hydrogen combustion produces no CO_2, its stabilizing effect on the flame enables higher EGR levels and, consequently, increased CO_2 concentration in the exhaust—an important consideration for post-combustion carbon capture efficiency.

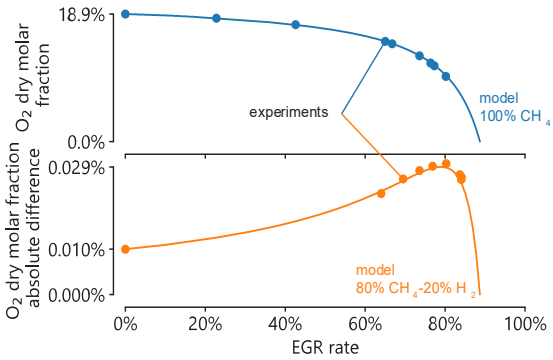

Fig. 3. Measured dry O_2 molar concentration and analytical prediction for methane across different EGR levels. The lower panel shows the absolute deviation from the methane baseline for each fuel blend.

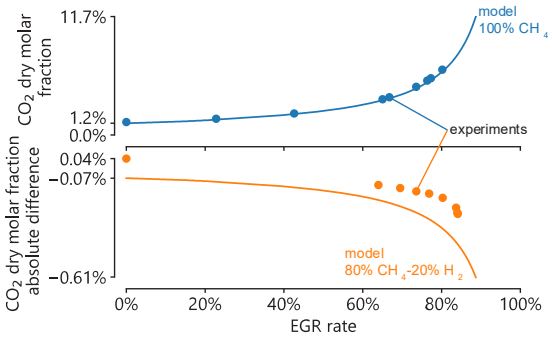

Fig. 4. Dry CO_2 molar concentration in the exhaust as a function of EGR rate for methane and 20% H_2 blend.

2.2 NO_x Emissions

NO and NO_2 concentrations were measured at the exhaust (17) using the Testo 350 ® gas analyser. Since fuel composition affects combustion characteristics and resulting recirculation ratios, NO_x concentrations are plotted against dry CO_2 content rather than EGR rate to allow for meaningful comparison.

Figure 5 reveals a characteristic NO_x trend: concentrations rise with increasing CO_2 until peaking around 20 ppm at 4% CO_2, after which they decline. Their production is attributed to thermal NO_x formation via the Zeldovich mechanism, which is highly sensitive to combustion temperature. What is about the behaviour of the evolution, EGR initially increases the residence time of reactants, thereby promoting NO_x formation. At higher EGR levels, the oxygen depletion reduces NO_x emissions. Nevertheless, a detailed combustion analysis would better allow to understand the thermal contribution of H_2 combustion in the chamber.

Importantly, the fuel composition has a negligible effect on NO_x emissions in this configuration. Due to the high global dilution inherent to mGTs, the combustion process avoids the formation of hot spots, which are primary sources of NO_x. Additionally, neither methane nor hydrogen contain nitrogen, ruling out fuel-bound NO_x formation. Consequently, the addition of 20% hydrogen does not significantly alter NO_x behaviour.

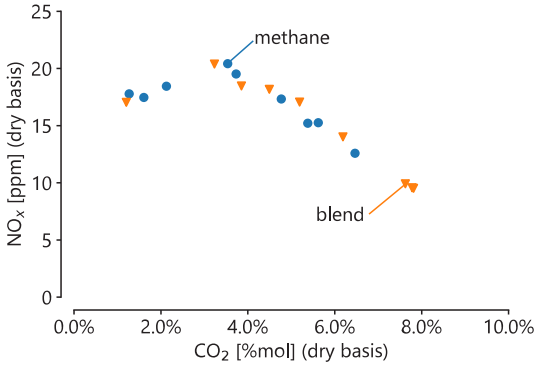

Fig. 5. NO_x concentrations (NO + NO_2) as a function of dry CO_2 content in the exhaust. Comparison between methane and 20% H_2 blend.

For this setup, EGR rates above 60% are clearly effective in mitigating NO_x emissions. Furthermore, as a portion of the exhaust is recirculated, the total exhaust mass flow rate decreases, thereby reducing the total mass of NO_x released to the atmosphere.

2.3 CO Emissions

CO emissions are also presented as a function of dry CO_2 concentration (Figure 6) to facilitate comparison across fuels. An exponential increase in CO concentration is observed with increasing CO_2, which corresponds to higher EGR levels. This trend reflects the oxygen-deficient conditions in the combustion chamber, which favour incomplete combustion and the formation of CO.

Micro gas turbines typically employ a staged combustion chamber, where only about 30% of the total air enters the primary zone. At high EGR levels, this zone quickly becomes sub-stoichiometric, exacerbating CO formation. Additionally, the recirculation of CO_2 itself can lead to dissociation and secondary CO production. As outlined by Masri et al. [10] several pathways contribute to CO formation, including reactions catalysed by third bodies such as CO, CO_2, H_2, H_2O, N_2, and O_2.

As shown in Figure 6, the inclusion of 20% hydrogen in the fuel blend significantly reduces CO emissions. Since CO emissions are typically the limiting factor in achievable EGR rates, this reduction is especially relevant. For a given CO threshold, hydrogen co-firing enables an increase of 1–2.5% in dry CO_2 concentration—thus improving the feasibility of carbon capture.

This improvement is largely due to two factors: (i) the lower carbon-to-hydrogen ratio in the fuel, and (ii) the enhanced reactivity of hydrogen, which promotes the formation of hydroxyl radicals (OH•). These radicals play a crucial role in oxidizing CO into CO_2, as described by the Equation 17.

$$CO + OH\bullet \rightarrow CO_2 + H\bullet \quad (17)$$

Moreover, as previously seen in Figure 3, the presence of hydrogen increases the oxygen concentration in the exhaust, which implies a greater availability of oxygen at the combustion inlet—further promoting complete oxidation and minimizing CO formation.

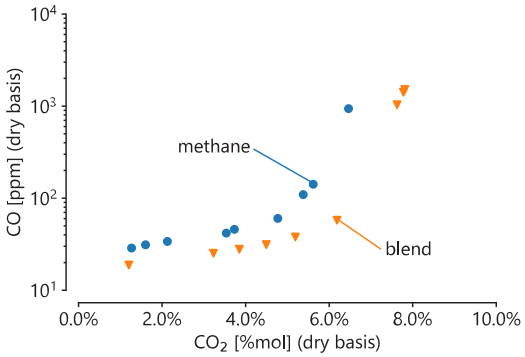

Fig. 6. CO concentrations as a function of dry CO_2 content in the exhaust. Hydrogen addition significantly reduces CO emissions at equivalent CO_2 levels.

Conclusion

Exhaust gas recirculation (EGR) has been widely recognized as an effective strategy to mitigate the energy and cost penalties associated with post-combustion carbon capture (PCC). However, its application remains constrained by the increase in

carbon monoxide emissions at high recirculation rates. Hydrogen co-firing has emerged as a promising solution to stabilize combustion and reduce CO formation, yet its effect on pollutant emissions—particularly CO and NO_x—required further clarification.

In this study, a 3 kW_e EnerTwin ® micro gas turbine was experimentally modified to enable extended EGR operation while being fueled with either pure methane or a 20% vol. hydrogen–methane blend. As expected, increasing the EGR level enhanced the CO_2 molar fraction in the exhaust while reducing the O_2 concentration. Notably, the maximum CO_2 concentration attainable with methane alone was 6.5%, whereas the hydrogen-enriched blend enabled operation up to 7.8%.

NO_x emissions were not significantly affected by the presence of hydrogen, due to the inherently high dilution and absence of fuel-bound nitrogen in both blends. In contrast, CO emissions showed a marked improvement: for a fixed CO emission threshold, the hydrogen blend allowed an additional 1 to 2.5% (absolute) increase in CO_2 concentration—demonstrating its effectiveness in extending the EGR range while maintaining acceptable pollutant levels.

Given that no substantial retrofit is required for hydrogen contents up to 20% vol., co-firing presents a viable strategy to enhance EGR applicability in micro gas turbines. These findings suggest that further exploration of hydrogen blending could yield valuable insights into the relationship between hydrogen content and CO mitigation, particularly for optimizing carbon capture performance in small-scale distributed energy systems. For larger GTs, similar trends can be expected regarding to CO depletion however the impact of hydrogen on NO_x formation should be deeply studied as they are working at higher temperature.

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