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Limitations of using hydrogen as a sustainable fuel in gas turbines

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Abstract

Hydrogen is increasingly regarded as a potential low-carbon fuel for gas turbine applications due to its ability to eliminate carbon dioxide emissions at the point of combustion. Despite this advantage, the large-scale implementation of hydrogen in gas turbines faces several significant technical and economic limitations. This study examines the limitations of hydrogen applicability in gas turbines by reviewing the relevant literature. One of the primary challenges arises from hydrogen's combustion characteristics, including its high flame speed and wide flammability range, which increase the risk of flame flashback and combustion instability. These issues necessitate substantial modifications to conventional gas turbine combustor designs and advanced control systems. In addition, hydrogen combustion typically results in higher flame temperatures compared to conventional hydrocarbon fuels, leading to increased formation of nitrogen oxides (NO_x). Meeting strict emission regulations requires complex mitigation strategies, such as lean premixed combustion or diluent injection, which can reduce efficiency and raise system complexity. Material compatibility is another critical concern, as hydrogen can cause embrittlement in metallic components, potentially compromising the structural integrity and long-term reliability of turbine systems. Furthermore, hydrogen's low volumetric energy density poses challenges for fuel storage and delivery, requiring high-pressure or large-volume storage solutions that are not easily compatible with existing gas turbine infrastructure. Finally, the economic feasibility of hydrogen-fueled gas turbines is constrained by the high cost of low-carbon hydrogen production and the limited availability of hydrogen transport and distribution infrastructure.

Keywords
hydrogen, gas turbine, sustainable fuel

1. Introduction

Hydrogen (H_2) is often presented as a promising alternative fuel in the transition toward low-carbon energy systems, particularly for its potential to achieve near-zero carbon dioxide emissions at the point of use (Petrović et al., 2025). Gas turbines, widely employed in power generation and aviation, are frequently considered suitable candidates for hydrogen combustion (Bagdi et al., 2023). However, despite its environmental appeal, hydrogen faces significant technical, economic, and operational limitations when used as a fuel in gas turbines (Kayfeci et al., 2019).

Hydrogen is the lightest element and exists as a diatomic gas with a very high energy content per unit mass but a low energy density per unit volume. It burns cleanly with oxygen, producing only water vapour, making it an attractive zero-carbon fuel (Muhssen et al., 2024). Its fast combustion chemistry and wide flammability range enable stable lean premixed combustion, particularly in gas turbines. Key benefits include zero CO_2 emissions, non-toxicity, and the possibility of renewable production via electrolysis (Németh et al., 2025). However, several challenges arise during the application of hydrogen as a fue in gas turbines. This study reviews the most important problematic aspects.

2. Limitations of hydrogen application in gas turbines

However, challenges such as NO_x formation at high temperatures, storage difficulties, and material issues, such as hydrogen embrittlement, remain (Bukovácz et al., 2025). Ongoing research focuses on adapting turbine combustors (Dişlitaş et al., 2025), improving flame stability, reducing emissions, and developing more efficient storage and injection systems (Zöldy and Kondor, 2021), with major companies already testing hydrogen-capable turbines for future power generation and aviation (Kondor I.P., 2025).

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Recent studies show that hydrogen-containing fuel blends can be stably burned under gas turbine–relevant conditions, particularly when blended with ammonia or natural gas (Onorati et al., 2022). Experiments confirmed that hydrogen improves flame stability, while combustion behaviour and NO_x emissions depend strongly on fuel composition and equivalence ratio. Although hydrogen offers clear advantages such as zero-carbon emissions and high energy content, it also introduces challenges, including higher NO_x formation and flashback risks. Proposed mitigation strategies include fuel dilution, exhaust gas recirculation, and advanced combustor designs (Habib et al., 2024). Even small hydrogen additions to natural gas can significantly reduce CO and NO_x emissions and improve efficiency, though exergy efficiency may slightly decrease and costs may increase. Currently, most gas turbines operate with hydrogen blends rather than pure hydrogen; typically, up to about 30% hydrogen can be used in conventional DLE (Dry Low Emission) combustors. Pure hydrogen combustion is still under development, with advanced concepts such as Mitsubishi's Multi Cluster Combustor enabling hydrogen and ammonia combustion in next-generation gas turbines (Carusotto et al., 2025).

In today's data-driven mobility landscape, the transition toward sustainable transportation increasingly requires a diversified portfolio of energy carriers rather than reliance on a single fuel (Zöldy and Baranyi, 2023). As digital monitoring, predictive modelling and system-level optimisation reshape how vehicles and infrastructure operate, different alternative fuels – such as hydrogen, electricity, synthetic e-fuels and advanced biofuels – each offer distinct advantages for meeting environmental targets, operational demands and sector-specific needs (Bernalte, 2023). Hydrogen exemplifies this complexity: while it offers near-zero carbon emissions and favourable combustion characteristics, its technical and economic challenges highlight why no single energy vector can fully address the requirements of future mobility systems. Instead, sustainable mobility will depend on the intelligent integration of multiple fuel pathways, guided by data, supported by robust research, and optimised for efficiency, safety and resilience. The combustion characteristics of hydrogen not only influence flame stability but also significantly affect pollutant formation, particularly nitrogen oxides (NO_x). For this reason, the following section discusses the emission-related challenges associated with hydrogen combustion in gas turbines.

In practical applications, hydrogen is rarely introduced directly as a pure fuel in existing gas turbines. Instead, hydrogen is typically first blended with natural gas in gradually increasing concentrations. These hydrogen–natural gas blends allow operators to reduce carbon emissions while maintaining compatibility with current turbine hardware. Pure hydrogen combustion, on the other hand, represents a longer-term technological objective that requires substantial redesign of combustors due to hydrogen's high flame speed, wide flammability range, and increased risk of flashback.

2.1 Flashback mechanism

One of the primary challenges of hydrogen combustion in gas turbines is its combustion behaviour. Hydrogen exhibits a laminar flame speed of approximately 2–3 m/s, which is nearly an order of magnitude higher than that of methane (~0.35–0.45 m/s). This significantly increases the risk of flashback in premixed combustors. Flashback refers to the undesired propagation of a flame back into the burner, leading to combustion within the premixing section. This phenomenon is an inherent characteristic of all premixed combustion systems, including gas turbine combustors. A flashback occurs when the local flame-propagation speed exceeds the velocity of the incoming flow in regions where the fuel–air mixture is within flammable limits (Flebbe et al., 2024).

While the properties of hydrogen can enable stable combustion at low fuel concentrations, they also increase the risk of flashback, where the flame propagates upstream into the burner. Flashback can severely damage turbine components and compromise operational safety, requiring substantial redesign of combustor systems and the implementation of advanced control strategies (Utschick et al., 2016).

2.2 NO_x formation

Another major limitation is nitrogen oxide (NO_x) emissions. For hydrogen combustion, thermal NO_x formation can exceed 50–70 ppm at turbine inlet temperatures above 1700 K, unless dilution or lean premixing strategies are applied. Although hydrogen combustion does not produce carbon dioxide, the high flame temperatures associated with hydrogen significantly promote thermal NO_x formation (Nyerges, 2026). Meeting stringent emission regulations, therefore, becomes challenging without sophisticated mitigation techniques such as lean premixed combustion, exhaust after-treatment, or steam and water injection. These solutions add complexity, reduce overall efficiency, and increase operational costs. Earlier research by Kondor (2026) showed that lean operation generally reduces NO_x formation because the average flame temperature decreases with excess air. However, lean flames can increase the effective residence time of gases in the hot zone, potentially

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leading to higher local peak temperatures. Reduced flame quenching results in fewer cold regions interrupting the high-temperature zone. In a small, highly preheated combustion chamber, even lean flames can sustain very hot cores if they become more compact. In addition, mixture stratification can create locally stoichiometric regions (Kondor I.P., 2025).

2.3 Metal embrittling

Material compatibility presents an additional obstacle. Hydrogen can embrittle certain metals, weakening structural components over time. Gas turbines operating with hydrogen require specialised materials and coatings to withstand hydrogen exposure, high temperatures, and pressure cycling. This not only increases manufacturing costs but also raises concerns about long-term durability and maintenance requirements (Pomeroy, 2005). Hydrogen embrittlement in turbine alloys is primarily associated with hydrogen-enhanced localised plasticity (HELP) and hydrogen-enhanced decohesion (HEDE), which promote micro-crack initiation along grain boundaries under cyclic thermal stresses.

2.4 Energy density

From an energy density perspective, hydrogen also poses practical limitations. Although it has a high gravimetric energy density, its volumetric energy density is very low, especially in gaseous form. As a result, hydrogen requires significantly larger storage volumes or high-pressure systems compared to conventional fuels. This complicates fuel infrastructure, particularly for existing gas turbine installations that were not designed for hydrogen use. A comparison of the parameters of methane and hydrogen is summarised in the table below.

Table 1 Comparison of the main parameters of methane and hydrogen

Parameter	Hydrogen	Methane
Laminar flame speed	~2-3 m/s	~0.35-0.45 m/s
Ignition energy	~0.02 mJ	~0.28 mJ
Autoignition temperature	~585 °C	~540 °C
NO_x emission potential	2–3× higher	baseline

While the physical and chemical properties of hydrogen determine its combustion behaviour, the practical utilisation of hydrogen in gas turbines depends strongly on the design of the combustion system. The following section reviews the main gas turbine combustion technologies and their compatibility with hydrogen fuels.

3. Solutions

The most commonly used fuel-air mixing method in gas turbines is an air swirler that creates turbulence (Figure 1). There are several methods to mitigate the flashback phenomenon. One is controlling autoignition, which can be achieved by reducing the flow rate or increasing the fuel/air temperature. These can be achieved by controlling the combustion chamber pressure with bleed valves (Gupta, 1997):

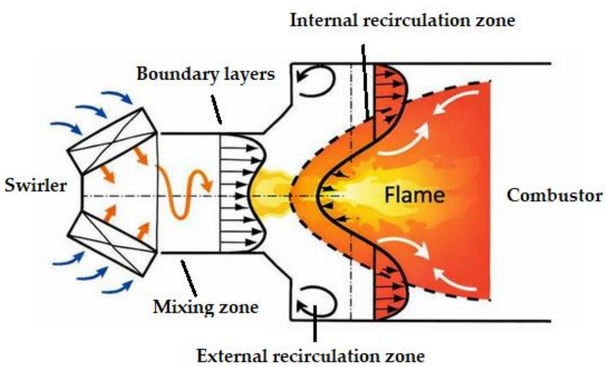

Figure 1. Premix swirl combustion chamber

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Several solutions have been developed to reduce NO_x emissions. One of the most common solutions is lean premixed combustion with dry low NO_x (DLN)/dry low emission (DLE), or a secondary (post-combustion) selective catalytic reduction (SCR) method. DLE combustors are designed to reduce NO_x emissions by operating under lean premixed combustion conditions without the use of water or steam injection. By carefully controlling the fuel–air mixing and maintaining lean operation, DLE combustors lower the average flame temperature, which suppresses thermal NO_x formation. However, this requires precise control of flame stability, as lean combustion is more sensitive to flashback, blow-off, and combustion instabilities (Stuttaford and Rubini, 1997). A schematic diagram of the lean combustion chamber is shown in Figure 2.

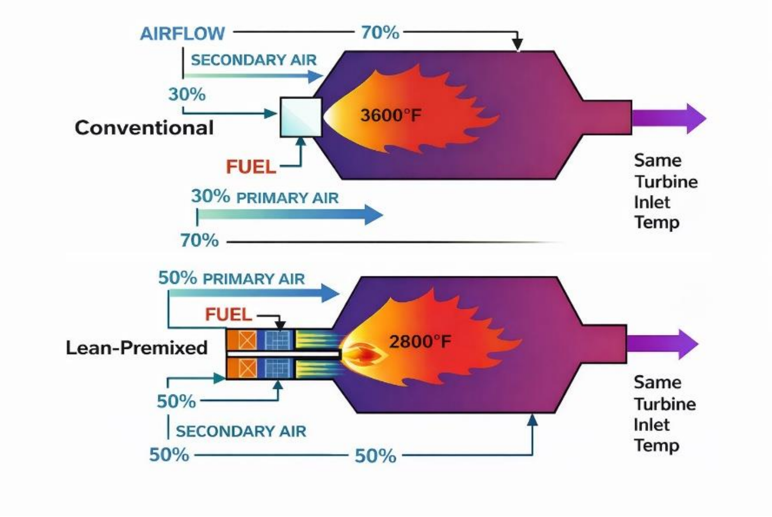

Figure 2. Conventional and lean-premixed combustor

Fully premixed hydrogen flames exhibit the highest flashback risk due to their high flame propagation speed, whereas diffusion flames are inherently more stable but produce significantly higher thermal NO_x emissions. (Szwaya et al. 2013) The comparison of combustion instabilities in hydrogen turbine flames is summarised in Table 2.

Table 2. Combustion instabilities in hydrogen turbine flames

Flame type	Flashback risk	Stability
Fully premixed	very high	good mixing but unstable
Partially premixed	medium	compromise
Diffusion flame	low	high NO_x

4. Conclusion

Hydrogen offers considerable potential as a low-carbon fuel for gas turbines, as it can eliminate carbon dioxide emissions at the point of combustion. Several technical and economic challenges currently constrain its practical application. Hydrogen's high flame speed and wide flammability range significantly increase the risk of flashback and combustion instability, requiring advanced combustor designs and precise control strategies. The high flame temperatures of hydrogen combustion promote increased NO_x formation, making compliance with emission regulations difficult without complex mitigation techniques that may reduce efficiency. Material degradation from hydrogen embrittlement, combined with hydrogen's low volumetric energy density, further complicate turbine durability, fuel storage, and infrastructure integration.

Overall, while hydrogen remains a promising option for sustainable power generation, its direct use in gas turbines faces notable limitations. In the short to medium term, hydrogen blending with conventional fuels appears to be the most practical approach, while the widespread use of pure hydrogen will depend on further technological and infrastructural development.

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