ELECTRIC POWER RESEARCH INSTITUTE

TECHNOLOGY INSIGHTS

A Report from EPRI's Innovation Scouts

Hydrogen-Capable Gas Turbines for Deep Decarbonization

THE TECHNOLOGY

Recent innovations in burner design and fuel staging enhance the capability of gas turbines to accommodate fuels with high hydrogen content. More work is needed to develop and validate turbine components and systems suitable for 100% hydrogen combustion.

THE VALUE

Robust low-NOx gas turbines capable of producing power from low-carbon fuels such as hydrogen could enable natural gas assets and infrastructure to be leveraged as a resource for decarbonization within the integrated energy network.

EPRI'S FOCUS

EPRI is tracking progress by gas turbine manufactures in developing high-hydrogen-capable components and systems and is exploring opportunities for research, collaborative technology evaluations, site assessments, and demonstrations.

INTRODUCTION

Deployment of new, high-efficiency natural gas generation assets has accelerated in recent years, due both to low fuel prices and to the need for greater operating flexibility to accommodate growth in variable-output renewable electricity supply. This trend has contributed to unprecedented reductions in carbon emissions from the U.S. electricity sector (primarily due to replacement of more carbon-intensive coal assets).

With ambitious emission reduction policies being rolled out in many countries and U.S. states and many utilities pledging to achieve substantial reductions within the 2040-2050 timeframe, substantial investment in the deployment of new low-carbon resources is anticipated in the decades ahead. While coal-to-gas switching, renewable generation, energy storage, transportation and heating electrification, and demand response technologies are expected to play important roles in the near term, at-scale deployment of novel low-carbon technologies on the grid—including low-carbon fuels (such as hydrogen (H_2) and ammonia (NH_3))—may be needed to achieve *deep* decarbonization of the power sector by 2050.

This brief focuses on the status and decarbonization potential of gas turbines capable of reliable, high-performance operation on fuels containing up to 100% hydrogen (see Box 1)

HYDROGEN SUPPLY

Historically, industrial-scale H_2 production has involved steam methane reforming (SMR) of natural gas, with CO_2 representing a major by-product of this energy-intensive process. H_2 also can be produced through electrolysis, where electricity is used to split water into H_2 and oxygen (O_2).[1] Sometimes referred to as "power-to-gas" (P2G), this process is similarly energy-intensive, but it generates no carbon emissions. When the electricity used to power the electrolyzer comes from a low- or no-carbon source, the resulting H_2 is also a low- or no-carbon fuel.

According to the IEA, over 200 projects converting electricity to H_2 have been commissioned since 2000.[2] Major near- and long-term drivers include the anticipated availability of low-cost renewable electricity and

Box 1: Emissions Reductions from Hydrogen Fuels

Combustion of hydrogen (H_2) produces no carbon dioxide (CO_2) emissions. Hydrogen-containing fuels thus can reduce carbon emissions when fired in gas turbine (GT) generation assets, depending both on how the hydrogen is produced and on the amount of hydrogen in the fuel.

Hydrogen can contribute to lower-emissions gas turbine power generation because it is a potentially near-zero-carbon fuel. Combustion of hydrogen produces no carbon dioxide (CO_2) emissions, and H_2 can be produced using very low emissions electricity generation from wind, solar, or nuclear plants. Gas turbine operation has been demonstrated with both 100% H_2 fuel and with H_2-natural gas (NG) blends. H_2/NG fuel blends are a possible approach for incremental decarbonization of natural gas generation assets.

Fuel blends with higher H_2 content—typically expressed on a volumetric basis—result in lower CO_2 emissions per MWh, but the relationship is nonlinear (as shown in Figure 1).

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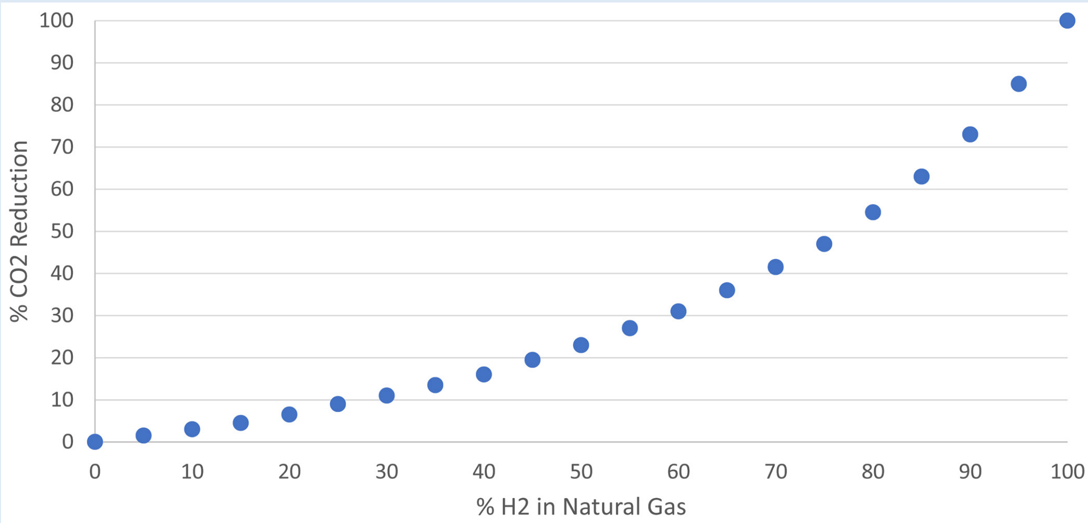

Figure 1. CO_2 Reduction for H_2-NG blends by volume

the potential for P2G facilities to contribute to dynamic balancing, seasonal-scale storage, and other grid services. As shown in Figure 2, the number of projects and average scale of those projects has increased in recent years, indicating increasing economies of scale as electrolyzer technologies advance. H_2 has the potential to act as a storage medium for renewable electricity, enabling GT power plants to provide large-scale dispatchable generation using a low-carbon fuel.

Electrolyzers sited near or co-located with gas turbines could supply point-of-use H_2. Injection of H_2 into existing NG infrastructure for storage, distribution, and downstream consumption by a range of end users, including in buildings and at power generation facilities, is being explored by many governments—and also by some gas utilities—as a method for incremental decarbonization of the NG sector. Ongoing research on pipeline injection focuses on understanding and mitigating materials-related challenges, as well as on assessing the impact of blended fuels on various end users.[3]

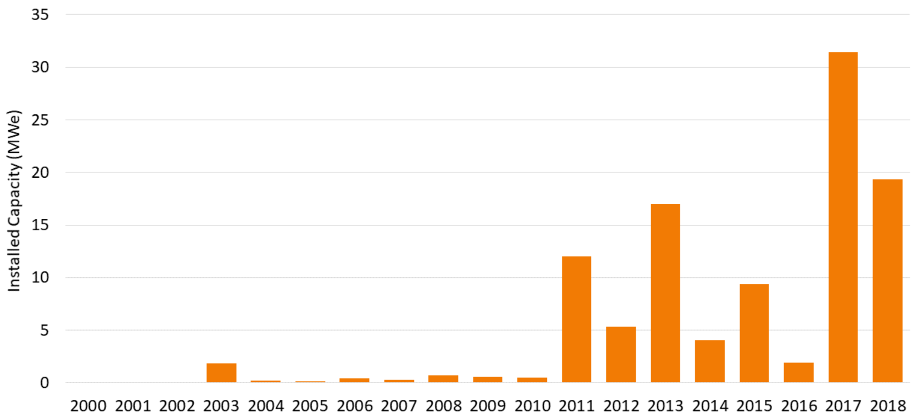

Figure 2. Global Electrolytic Hydrogen Production Capacity by Deployment Year [Source: IEA Hydrogen Project Database]

Box 2: Recent History of Major Hydrogen Combustion Efforts in the U.S.

R&D relating to combustion of H_2-containing fuels for power generation applications has focused on coal-derived syngas produced and fired at integrated gasification combined cycle (IGCC) plants. After 2000 and in response to rising natural gas prices, the U.S. Department of Energy (DOE) invested in extensive R&D to advance the production and utilization of syngas, which usually contains CO, H_2, and CH_4 along with inert gases such as nitrogen (N_2) and CO_2. Interest in coal-derived syngas has waned since the onset of the shale gas boom, and only a handful of IGCC plants are operational in the U.S. However, much of the previous work leading up to DOE's current Advanced Combustion Turbines program[4] remains applicable to non-syngas hydrogen-fueled power generation.

CHALLENGES FOR USE OF HYDROGEN AS A GT FUEL

Hydrogen combustion is not a new topic. For many decades, R&D has been performed to understand the characteristics of a range of H_2-containing fuels (see Box 2).

Additionally, hydrogen generated as an industrial by-product has long been used in industrial gas turbines, with more than a hundred units world-wide having operated on hydrogen-containing fuel blends.[5,6] These turbines typically have been older class technologies utilizing diffusion (non-premixed) and wet low-NOx combustion configurations.

Today's state-of-the-art, high efficiency gas turbines use dry low NOx (DLN) combustors designed for burning NG with extremely low NOx and CO emissions. The fuel flexibility of these designs is continuing to be expanded pushing upwards of 50%+ hydrogen (depending on the specific model). Further R&D is needed to advance fuel flexibility capabilities to span the full range of 0-100% H_2.

Fundamentally, the challenges of using hydrogen-containing fuels for power generation with standard turbine technologies result from the differences in combustion characteristics of H_2 compared to CH_4 [see Table 1]. For example, the *flame temperature* (or reaction temperature) of H_2 is about 5-10% higher, potentially leading to higher thermal NOx production—and creating challenges related to degradation of materials and coatings. Due to the substantially lower volumetric energy density (i.e. lower heating value) of hydrogen compared to methane, fuel supply lines and other system components may need resized to account for the increased volume of fuel needed to maintain the same power output.

Another marked difference, and one of the most technically challenging, is the faster flame speed of hydrogen. For example in a DLN combustion system, flow velocity would need to be nine times higher to prevent the flame from flashing back—the unintentional propagation of the flame upstream into the premixing combustion hardware. At about 95% H_2, the upper (flashback-driven) limit of a turbine's operating range experiences a relatively large decrease.[7] This narrows the stable operating range, presenting one of the biggest challenges to designing high hydrogen-capable premixed DLN systems.

Table 1: Hydrogen Properties

Property	Properties of H_2 (relative to NG)	Potential impact	Potential technical solutions
Carbon monoxide production	100% reduction	• CO production removed as a limitation to operating parameters	N/A
Energy density	Vol: <1/3 Mass: ~2.5x higher[7,8]	• More fuel by volume for same heat released	• Increased flow velocity
Flame speed	9x higher[7]	• Increased flashback risk	• Increased flow velocity • New fuel injection designs (e.g., fuel staging/ micromixers)
Flame temperature	~5-10% increase[7]	• Increased thermal NOx production; • Increased materials/coating degradation	• Larger selective catalytic reduction bed to compensate; fuel staging/new combustion designs • New materials/coatings
Lean blowout (LBO) limits	~50% increase in LBO margin[7]	• Increased turndown capability	N/A
Lower flammability limit	20% lower[9]	• Safety – more flammable in event of leak • More challenges to detection	• New leak detection methods/ gas sensors
Molecular size	8x lighter	• Increased tendency to leak	• More welded connections, new seals/tighter connections

Box 3: Demonstrating 100% H_2

As part of the Netherlands' Carbon-Free Gas Power project, Nuon (a subsidiary of Vattenfall) is scheduled to complete the conversion of one of three gas turbines at its Magnum power plant to 100% H_2 operation by 2024. The unit will use a modified MHPS diffusion combustion system (M701F CCGT 440 MW)[14] without steam or water injection.[6] Estimated to reduce the plant's CO_2 emissions by 2 Mt/year, this pilot project is a major step for utility-scale H_2 combustion in gas turbines.

On the other hand, the *LBO limit*—the lower limit of a turbine's operating range—gradually decreases with increasing H_2 content, and CO production is not a concern. These properties potentially enable improved turndown capabilities (the ability to run at lower-than-rated power output) relative to current NG GTs. This potentially improved turndown capability is a flexibility advantage that can support a more integrated energy network.

PROGRESS BY GAS TURBINE MANUFACTURERS

In recent years, original equipment manufacturers (OEMs) have been increasing the fuel flexibility of DLN turbine technologies, which are the current power industry standard. In most cases, existing DLN technologies can accommodate blended fuels with lower H_2 content (~<20%-30%), and advanced DLN combustion systems are emerging to enable higher-H_2 fuels. To combat flashback concerns, these advanced designs incorporate new burner aerodynamics and fuel staging strategies.

New burner designs that increase the axial velocity of premixed fuel/air stream into the combustion zone can help mitigate flashback concerns associated with hydrogen's high flame speed. One approach involves variations on micromixers—referred to as multi-tube mixers by GE (Figure 3) and multi-cluster combustors by Mitsubishi Hitachi Power Systems (MHPS)—that rely on axial flow alone for flame stabilization, whereas conventional DLN designs employ a swirling flow component. Due to the wider distribution of axial velocities in the combustion chamber, a wider range of fuels—including fuel components with different flame speeds (e.g. both CH_4 and H_2)—can be stabilized with micromixer configurations.

Figure 3. GE/DOE Micromixer

For example, GE's H_2-capable micromixers development efforts—carried out under the DOE National Energy Technology Laboratory's Advanced Combustion Turbines program that dates back to IGCC work in 2005—has culminated in a new burner design, DLN 2.6e, that can reportedly handle up to 50% H_2.[5,10,11]

Another approach to utilizing high-H_2 fuels is axial fuel staging (AFS). This strategy relies on distributed fuel and/or air injection, modifying the conventional DLN designs that introduce air/fuel only at the beginning of the combustion chamber by also injecting air/fuel at various downstream locations. The resulting combustion occurs in multiple "zones", allowing for lower local flame temperature (mitigating NOx production) and a lower initial *equivalence ratio*, which locally decreases the flame speed (mitigating flashback risk).

For example, Ansaldo Energia, in partnership with PSM, has developed an AFS-based retrofit combustion system for hydrogen fuels called FlameSheet™ that is compatible with DLN turbines from major manufacturers. Ansaldo has also integrated sequential combustion technology into design of its GT26 and GT26 turbines.[12] GE has also incorporated a combustor with AFS, called DLN 2.6+, into its HA line of turbines[13] for increased turndown capabilities and lower emissions.

Multiple gas turbine OEMs are working on new gas combustion technologies like micromixers and axial fuel staging, as detailed in Table 2. While the industry is beginning to put these high-hydrogen enabling components to use, primarily to increase efficiency and reduce NOx/CO emissions associated with natural gas-fired power generation, more work is needed to build upon these technologies to accommodate the full range of H_2-containing fuels, and to demonstrate these innovations at utility scale (see Box 3). Notably, EUTurbines, an association of European turbine manufacturers that includes the four OEMs listed in the table as well as other major vendors, is committed to making gas turbines capable of operating with 100% H_2 commercially available by 2030.[15]

NEXT STEPS AND COLLABORATIVE OPPORTUNITIES

While lower-percentage H_2-containing fuels are compatible with many current gas turbine systems with minimal-to-no hardware modifications, additional (but not insurmountable) technical obstacles exist on the path to widespread deployment of robust, low-NOx gas turbines suitable for 100% H_2 combustion.

The surge of global activity in low-carbon H_2 production and use, the growth in the role of NG infrastructure in supplying electricity, and the proliferation of government and industry commitments to a low-carbon future highlight the potential opportunities for large-scale H_2-based electricity generation and a corresponding need for R&D and field demonstration of high-hydrogen-capable gas turbine technologies.

This work cuts across multiple domains of expertise at EPRI and its global utility members.

Potential EPRI global RD&D areas could include site assessments of GT plants using hydrogen-containing fuels, technology evaluations and demonstrations, and evaluations of life-cycle impacts on system components including gas turbine and heat-recovery steam generator components. Other potential topics for exploration include limitations on turndown capabilities, impacts from additional water emissions on gas turbine downstream components, and potential safety impacts associated with use of high to 100% hydrogen fuels. Collaborators can benefit from sharing of lessons learned to support accelerated deployment of hydrogen-capable gas turbine systems. EPRI's collaborative model also can enable engagement by utilities and turbine OEMs across the

Table 2: Available OEM Capabilities and Future Plans [23,17,18,22,5]

	Type	Notes	TIT C(F) or Class	H_2 %(Val)
MHPS	Diffusion	N_2 Dilution, Water/Steam Injection	1200~1400 [2192~2552]	up to 100
	Pre-Mix (DLN)	Dry	1600 [2912]	up to ~30
	Multi-Cluster	Dry/Under development – Target 2024	1650 [3002]	up to 100
GE	DLE	Aeroderivative		up to 5
	SAC	Aeroderivative		up to 30-85
	SN	Single Nozzle (Standard)	B, E Class	up to ~90-100
	MNQC	Multi-Nozzle Quiet Combustor w/N_2 or Steam	E, F Class	up to ~90-100
	DLN 1		B, E Class	up to ~33
	DLN 2.6+		F, H Class	up to ~15
	DLN 2.6e	Other models to be implemented	9HA	up to 50
Siemens	DLE	Aeroderivative		up to ~2-15
	WLE	Aeroderivative		up to ~15-100
	DLE		E Class	up to 30
	Diffusion	No NOx abatement	E Class	up to 100
	DLE		F Class	up to 30
	Diffusion	No NOx abatement	F Class	up to 100
	DLE		H Class	up to 30
	Diffusion	No NOx abatement	H Class	up to 100
	DLE		HL Class	up to 30
Ansaldo	Sequential	GT26	F Class	up to 30
	Sequential	GT36	H Class	up to 50
	ULE	Current Flamesheet™	F, G Class	up to 40
	New ULE	Flamesheet™ – Target 2023	Various	up to 100

H_2 value chain—including production, delivery, and end uses—in support of H_2's application as a low-carbon energy carrier for the future integrated energy network.

Glossary

Diffusion vs Premixed Combustion – For premixed combustors, air and fuel are mixed before injection into the combustion chamber. For diffusion combustors, fuel is injected independently into the combustion chamber with no control over air/fuel ratio in the flame zone.

Equivalence ratio (ϕ) – The ratio of the actual fuel-to-air ratio to the stoichiometric fuel-to-air ratio. Thus, $\phi = 1$ is a stoichiometric mixer, $\phi < 1$ is fuel lean, and $\phi > 1$ is fuel rich.

Flame speed – The measured rate of flame front propagation (inversely related to the reaction rate).

Flammability range – The range of concentrations of a gas in air at which the mixture can ignite (delineated by upper and lower flammability limits).

Flashback – Unwanted propagation of the flame upstream in the premixed fuel/air passage.

Lean blowout limit – The minimum fuel-air ratio at which a flame can be sustained. Below this limit, the flame extinguishes (i.e. lean blowout).

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