David Noble
Mem. ASME
Electric Power Research Institute,
1300 West W.T. Harris Blvd.,
Charlotte, NC 28262
e-mail: bnoble@epri.com

David Wu
Mem. ASME
School of Aerospace Engineering,
Georgia Institute of Technology,
635 Strong St NW,
Atlanta, GA 30318
e-mail: dwu9@mail.gatech.edu

Benjamin Emerson
Mem. ASME
School of Aerospace Engineering,
Georgia Institute of Technology,
635 Strong St NW,
Atlanta, GA 30318
e-mail: bemerson@gatech.edu

Scott Sheppard
Mem. ASME
Turbine Logic,
111 N Rengstorff Ave.,
Apt 1325,
Mountain View, CA 94043
e-mail: ssheppard@turbinelogic.com

Tim Lieuwen
Mem. ASME
School of Aerospace Engineering,
Georgia Institute of Technology,
1689 Fernleaf Circle,
Atlanta, GA 30318
e-mail: tim.lieuwen@ae.gatech.edu

Leonard Angello
Mem. ASME
Electric Power Research Institute,
3420 Hillview Ave.,
Palo Alto, CA 94304
e-mail: langello@epri.com

Assessment of Current Capabilities and Near-Term Availability of Hydrogen-Fired Gas Turbines Considering a Low-Carbon Future

A confluence of technology development, policy support, and industry investment trends is accelerating the pace of Hydrogen (H_2) technology demonstrations, increasing the likelihood of power sector impacts. In preparation for a large scale power sector shift toward decarbonization for a low carbon future, several major power equipment manufacturers are developing gas turbines that can operate on a high H_2 volume fuel. Many have H_2 capable systems now that range from 5% to 100% H_2. Units with 100% H_2 capabilities are either using a diffusion burner or some version of a wet low emissions (WLE) burner. Most dry low emission/dry low NO_x (DLE/DLN) technologies are currently limited to approximately 60% H_2 or less. Therefore, research is currently underway to develop low NO_x gas turbine combustion systems with improved Hydrogen capability. This paper provides an overview of the technical challenges of Hydrogen combustion and the probable technologies with which the manufacturers will respond.

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Introduction: Gas Turbines and Decarbonization

Due to ever changing demand needs along with implications of carbon reductions, gas turbine combustion faces a game changing future that will continue to drive major technological developments in the coming years. This paper assesses the state of the art capability of gas turbine combustion technologies for use with Hydrogen (H_2) fuels, which are applicable for both combined cycle (as seen in Fig. 1) and simple cycle units, all the while, keeping in mind the importance of gas turbines in the future for a resilient and reliable power grid.

With this in mind, according to the EIA (U.S. Energy Information Administration), about 35% of electricity produced in 2018 was produced via natural gas (NG) combustion in gas turbines (GT) or boilers, which is up from just 26% in 2017 [1]. As coal retirements continue to occur, this number will continue to increase as utilities seek to replace baseload requirements. Continued growth of GT capacity is predicted in the USA [2]. Thus, GTs will continue to perform an important role in power generation for many decades through baseload, cyclic, and peaking operations.

Thus, GTs will be a part of electricity generation for decades to come, but the question to start answering now is —how does the energy industry reduce, or even eliminate, carbon output? To start the process of answering this question requires an examination of trends in the industry with future predictions and possible strategies for continued reduction. To this point, NG burning GTs, along with solar/wind renewable installations, maintaining nuclear units, coal retirements, as well as increased consumer energy use efficiency, have paved the current U.S. electricity sector path to lower carbon emissions. Specifically, from 2005 to 2019, there was an overall U.S. power industry CO_2 emissions reduction of about 15%; this includes industry/buildings, transportation, and electricity sector contributions. During this time, the specific electricity generation sector realized an approximate 28% reduction alone even though during this same time reduction in sectors such as transportation were partially feasible through electric vehicles

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Fig. 1 Typical combined cycle gas turbine power plant (EPRI stock photo)

that increased demand on the power grid [3]. The continued path that EPRI would like to see for 2030 would be an additional twofold decrease in CO_2 emissions. Realistically this can be accomplished from continued coal retirements, new renewable installations, and new, more efficient GT installments—even with the possibility of additional nuclear retirements. However, as the industry looks further out, to continue overall U.S. energy CO_2 emissions reductions to targets such as 80%+ by 2050, bigger changes are needed, specifically related to cleaner dispatchable generation.

For the electricity generating sector, advanced nuclear and carbon capture and sequestration are additional avenues for accomplishing the continued reduction, but an additional path is eliminating carbon from the fuel altogether through the utilization of H_2 or ammonia (NH_3). Hydrogen combustion is not a new topic. It has for many decades been investigated to understand combustion characteristics and emissions from a range of H_2 containing fuels. Most prominently in recent history (c. 2000) was the directive to understand and use synthesis gas [syngas, coal derived fuel usually containing CO, H_2, CH_4, along with inerts like H_2O, N_2, CO_2, etc.…)] from an integrated gasification combined cycle (IGCC) [4,5]. During this time, the U.S. Department of Energy (DOE) invested millions of dollars to utilize H_2 containing fuels all the way to the current advanced combustion turbines program [6]. This R&D focus laid the groundwork for new designs and technologies that we see today such as micromixers and fuel staging. These technologies are emerging as the focus of many new engine designs.

The purpose of this paper is to overview the impact of decarbonized fuels on gas turbine combustion systems. The paper begins with a presentation of the challenges of combustor operability with decarbonized fuels. The paper closes with an overview of the openly published research and development that the original equipment manufacturers (OEMs) are exploring to respond to these challenges. The primary focus of the paper is on H_2 combustion, which the authors identify as the most likely decarbonized gas turbine fuel. This paper provides a broad overview of the many engineering challenges and solutions surrounding H_2 combustion with an extensive literature survey referenced for a deep dive into the details of these topics.

Challenges With Carbon Free Fuel Usage

The infrastructure for widespread H_2 fuel usage in gas turbines is presently unavailable. Implementation of a H_2 infrastructure must overcome several key safety related hurdles. The H_2 molecule has a greater tendency to leak than other gases. This is because the small H_2 molecules can squeeze through small cracks, gaps, and other tolerances that cannot accommodate a larger CH_4 molecule. Furthermore, H_2 embrittles many fuel plumbing materials [7], compromising many metals and materials commonly included in combustion and gas plumbing hardware. These compromised materials can introduce new leaks as well as cause premature failure of flow control and instrumentation equipment. A H_2 leak also brings greater hazard than a NG leak for several reasons. First, H_2 has a lower lean flammability limit (4% by volume at standard temperature and pressure (STP) in air) compared to CH_4 (5% by volume at STP in air). By mass, this translates to a lean flammability limit for H_2 in air that is only 10% that of CH_4. This means that a H_2/air mixture becomes flammable and can be ignited with lower fuel gas concentrations (i.e., an explosive mixture will build up sooner in a confined space such as enclosures and heat recovery steam generator (HRSGs)) than NG. This will have important purge considerations for failed starts. It might also require ventilation solutions for HRSG attics which could easily accumulate highly buoyant H_2 gas.

Hydrogen leaks are also hazardous because the chemiluminescence from premixed H_2 flames is nearly invisible. A common misconception is that H_2 flames are completely invisible; however, the hot gases that are produced in nonpremixed H_2 air flames in many leaks will emit some light [8]. The lower observability of H_2 flames relative to NG flames can make the avoidance of hot gases difficult for those who respond to or who happen upon a leak.

While the lack of H_2 fuel usage for GTs can be primarily attributed to limited H_2 availability, the complexity of using and burning H_2 is a close second. While H_2 combustion does have technological barriers, it boasts the smallest technological barriers to storage and clean use of renewable generation with existing infrastructure relative to other alternative carbon neutral fuels. It is already possible to use H_2 as a fuel, no matter the fuel constituent percentage as evidenced by current installations [10–12]. However, current challenges exist with dry,low NO_x (DLN) technologies pushing past 10 to 50% depending upon the hardware. Most high H_2 capabilities exist with either diffusion or wet-low NO_x type technologies, which are not comparable to the NO_x levels of DLN. Figure 2 outlines a brief comparison between nonpremixed (diffusion type) and premixed (DLN type) combustion systems.

Overall, these challenges primarily exist because of the vast differences in combustion characteristics in H_2 enriched fuels as compared to typical NG. For example, for a given set of combustor inlet conditions, the adiabatic flame temperature (or postflame temperature) is increased from 5 to 10% [13] with high H_2 fuels. This has two implications: (i) potential for higher NO_x and (ii) potential for material/coating issues. Another marked difference and one of the most problematic is that the flame speed is up to nearly an order of magnitude higher than NG [14]. Generally speaking, using the same conditions, a premixed, DLN nozzle would need 10 times higher flow velocity to prevent the flame from flashing back and damaging the hardware. Moreover, with the low flammability limits as compared to NG, as visualized in Fig. 3, at high H_2 content (>90% H_2), and no change in nozzle velocity, the lean blowout (LBO) and flashback limits allow for a narrow stable operating range [13]. From a detailed turbulent combustion perspective, lean H_2 combustion is fundamentally different than combustion of other lean mixtures. For example, lean H_2 flames are highly thermo-diffusively unstable, meaning that corrugations and wrinkles in the flame will tend to grow and become more pronounced. This is partially responsible for the enhanced turbulent flame speed of lean H_2 flames relative to other lean mixtures.

The lower heating value (LHV) of H_2 compared to methane (CH_4) is another consideration for the development of H_2 capable systems, see Table 1. With this difference in mind, a H_2 fired gas turbine would have to flow less than half of the mass flow of fuel compared to a CH_4-fired gas turbine. However, H_2 is eight times less dense than CH_4 at the same pressure and temperature.

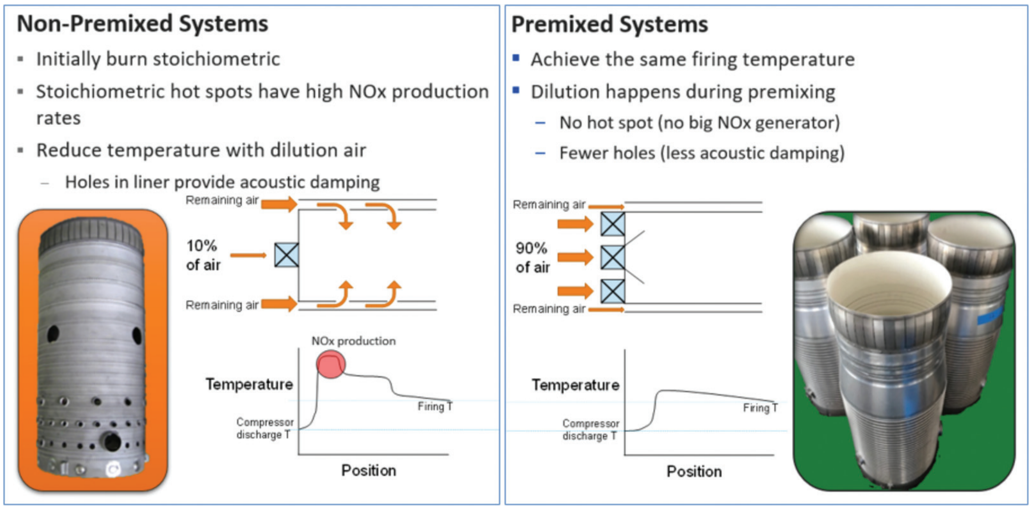


Fig. 2 Comparison of nonpremixed (left) to premixed systems (right) [9]

Therefore, its volumetric LHV is roughly a third of CH_4. Therefore, a H_2 fired gas turbine would need three times more fuel volume flow rate than a CH_4 fired plant. The volume flow rate sets the size of the plumbing, so the H_2 plant would need piping, valves, and instrumentation that are sized roughly three times bigger than the CH_4 plant.

Alternatively, the fuel gas pressure could be scaled as a function of H_2 content. For example, a pure H_2 fuel gas would need to be suppled at roughly three times the pressure to have the same volume specific heating value as CH_4 at the same temperature.

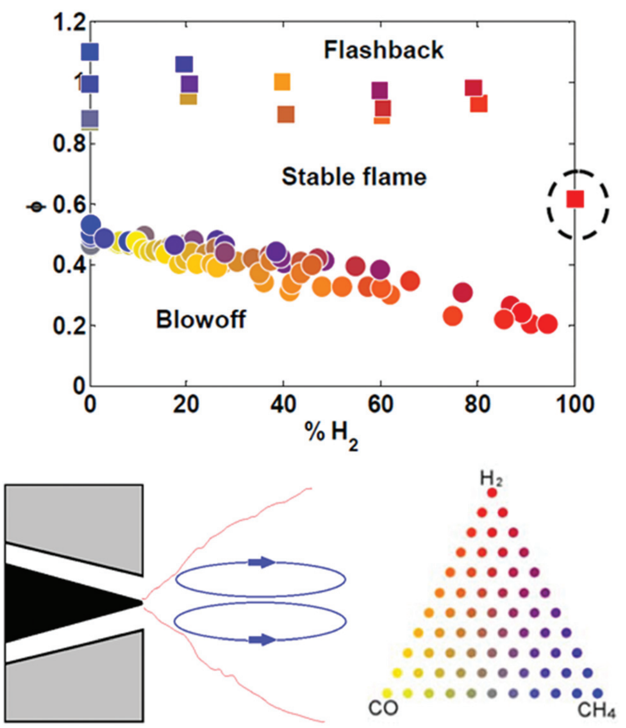


Fig. 3 Flashback/LBO limits of syngas (H_2 containing fuels) [top], flame stabilization example for this experimental [bottom left], and color coding for data fuel composition reference [bottom right] [13]. Squares indicate flashback boundaries, and circles indicate blowoff boundaries. Carbon monoxide-containing fuel mixtures (yellow/green/orange points) should be omitted for the purposes of this paper (reference color triangle for fuel composition insights).

With increased supply pressure or volume flow rate for a H_2 capable GT does have substantial cost and safety considerations especially considering retrofitting existing assets.

Another challenge is the desire for H_2 composition flexibility in power generation depending on the availability/cost of H_2. This leaves the same problems as illustrated previously but exacerbated due to the need to operate at both low and high flame speed conditions depending on fuel choice. This leads to the challenge to design a robust combustor that can operate with acceptable emissions on either H_2 or CH_4 (or more practically on a blend of CH_4 and H_2 with widely variable blend ratios). This challenge exists for premixed combustors because low flame speeds promote lean blowout, and high flame speeds promote flashback (only a concern for premixed combustors like those implemented in all lean premixed systems). However, premixed combustors (versus diffusion or nonpremixed combustors) are needed for their low NO*x* characteristics. Therefore, a premixed combustor with H_2 fuel flex must be designed to support a H_2 flame with flashback margin in the same hardware that can support a CH_4 flame with LBO margin. This leaves a thin, or possibly nonexistent, operating margin. The operating regime can be maximized by limiting the percentage of H_2 that can be implemented but that limits the benefits of a H_2 fuel flex capable GT. Additionally, from the earlier stated issue of supply the plumbing in a fuel flex system that is sized appropriately for H_2 would be over-sized/over-pressurized for CH_4 at the same conditions.

Combustion instabilities (also known as combustion dynamics) will also be a factor for H_2 combustion and fuel flexibility. The combustion instability phenomenon has the challenging feature that its characteristics are nonmonotonic with operating parameters (such as combustor inlet pressure, combustor inlet temperature, fuel gas composition, etc.). Therefore, it is not possible to say that H_2 combustion will make combustion dynamics "better" or "worse." Instead, the H_2 effect on combustion instabilities is anticipated to vary on a case by case basis. For example, combustion instabilities typically show up as "islands" in the operating space. Hydrogen addition may move these islands in the operating space relative to where they appear with NG combustion. This is likely to present a challenge for fuel flexibility, since different combustor tunes (i.e., fuel splits) will have to be established for different H_2 fractions to balance combustion instabilities against emissions.

The combustion properties of H_2 that this section has outlined for combustor design (flame speed) and safety (lean flammability limit and observability) are nonlinear with mixture fraction [16]. This means that H_2 addition to the gas supply can have minimal impact on these properties at low H_2 fractions, but that small increments of H_2 fraction can have drastic impacts on these properties at higher H_2 fractions. In reality, the effect of H_2 fraction on

Table 1 General hydrogen properties [15]

		Methane	Hydrogen
Molecular weight, g/mol		16.0	2.0
Density, kg/m^3	at STP	0.66	0.09
	at 500 psi, 300 F	15.8	2.0
Lower heating value	Mass specific, MJ/kg	50	120
	Molar, MJ/kmol	802	242
	Volumetric, MJ/m^3 at STP	33	11
	Volumetric, MJ/m^3 at 500 psi, 300 F	788	238

the turbulent burning properties of H_2/NG mixtures is still an area of active research.

Also, note this section is about carbon free fuels and while the discussion has been centered around H_2, another fuel type that is getting attention in a more limited purview is ammonia (NH3). Liquid NH3 is a much easier storage and transportation media than that of gaseous H_2. In fact, the agricultural industry already operates NH3 pipelines. However, the combustion considerations are much less favorable. Flame temperature and flame speeds are much lower for ammonia than NG as shown in Table 2 [17]. However, the Nitrogen content of the fuel has increased NO*x* potential, even in premixed conditions. Therefore, the primary focus for the remainder of this paper will be upon H_2 only. For additional works on ammonia usage in gas turbine combustors have been published by Kurata et al. [18] and Valera-Medina et al. [19].

Gas Turbine Original Equipment Manufacturers and Hydrogen

The last and most important series of questions to consider are a) what are the OEMs current capabilities with H_2 and b) what are they doing to enable H_2 capable GTs of the future? Over the next 10 years (2018 to 2027) it is estimated that an additional $107 billion in new GTs will be sold worldwide [2]. These projected numbers would equate to over 900 new GTs installed in North America during this time with a majority (based on capacity and value) being General Electric (GE) assets (See Fig. 4).

This section will present several emerging technologies that the various manufacturers have released in various publications. These technologies include various fuel staging and advanced mixing concepts. Utilizing manufacturer-published materials (including conference papers, reports, and patents), these complex combustion system concepts will be showcased below. The main objective of this section is to emphasize the recurring theme of fuel staging and advanced mixing technologies in the various forms that are surfacing among the different OEMs.

Table 2 Fuel properties comparison with hydrogen, methane, and ammonia [17]

Fuel	H_2	CH_4	NH_3
LHV (MJ/kg)	120	50	18.6
Flammability range (f)	0.1–7.1	0.5–1.7	0.63–1.4
Adiabatic flame temp (% difference)	7%	0%	−7%
Max laminar flame speed (cm/s)	291	37	7

Recently, GEs CMO (GE Power, Greenville, SC) Brian Gutknecht during a panel at the 2019 Edison Electric Institute Conference stated that he sees H_2 as a key factor for 100% carbon-free generation [20]. In fact, to this point GE has the largest in-service operating experience with H_2 containing fuels at 70+ in operation dating back over 30 years from IGCC to refinery and steel mill supplied gases [11]. This experience includes 25 GTs utilizing fuels with at least 50% H_2 by volume and examples of units such as a 6B.03 using fuel blends of 70 to 90% H_2. One specific example is a site in Italy (Fusina) utilizing a 41.6% efficient GE10 (a Baker Hughes GE gas turbine) combined cycle gas turbine plant (12 MW) operating with 96 to 100% H_2 [21]. This site accounts for an annual reduction of 17,000 tonnes of CO_2 for approximately 20,000 households. This site has been operated by ENEL since July 2010 and is equipped with diffusion style burners with abatement strategies (steam injection) for NOx reduction. Overall, this was a approximately 50 Million Euro investment generating an estimated 60 million kWh annually.

Moreover, U.S. DOE National Energy Technology Laboratory (NETL) funds have been utilized to develop micromixers that can handle high H_2 fuels. This work dates initially to IGCC work that began in 2005 [22,23]. This has culminated in a new burner design designated DLN 2.6e that uses micromixers (see Fig. 5) and can reportedly handle up to 50% H_2 [11,24,25]. The micromixer allows for increased axial velocity in exchange for the

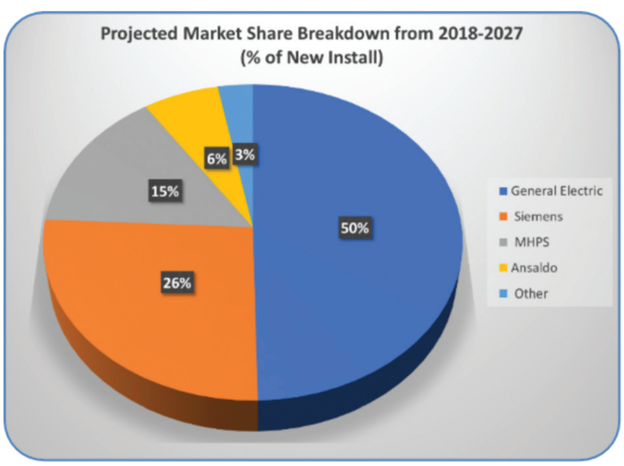


Fig. 4 Projected future market share of new gas turbines [2]

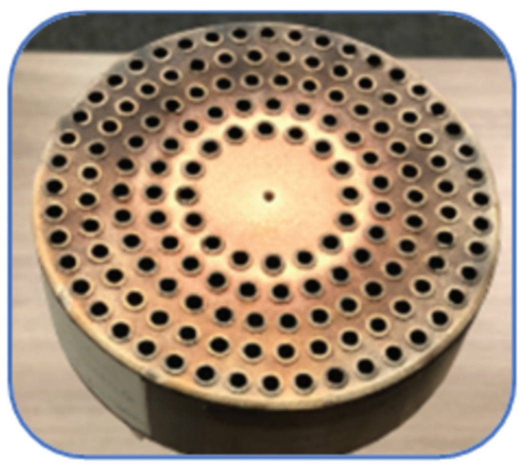


Fig. 5 Fuel injector concept showing a micromixer that would replace a conventional swirler [26]

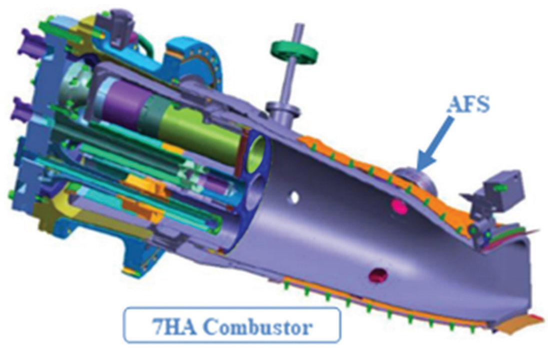


Fig. 6 GE AFS concept showing the fuel/air injection axial location point in the transition piece. Figure is reproduced from Ref. [27].

swirling flow component that is traditionally associated with DLN type technologies, thus the pressure loss is equivalent and not increased.

Less directly impactful, but just as holistically important, is the recent incorporation of axial fuel staging (AFS), which was introduced with the HA class units for increased turndown and lower emissions [27]. The AFS for H_2 systems would serve the same purpose as for NG systems: it allows for leaner main combustor operation, therefore, lessening high NOx production and flashback concerns for the main combustion zone (Fig. 6).

Likewise, Siemens has demonstrated H_2 capability in its current gas turbine fleet. Siemens advertises its fleet's H_2 capabilities in its July 2019 Hydrogen Combustion Sales Information brochure [28]. It claims up to 80% H_2 capability in its dry low emission (DLE) systems with the SGT-600, and up to 100% H_2 capability in some of its Wet Low Emissions aeroderivative engines (SGT-A65, SGT-A45, SGT-A35). Siemens aeroderivatives have operated with more than 100,000 h on fuels containing up to 78% H_2. These units can handle substantial Wobbe index (NG composition) variation, including real-time gas composition swings. However, many of these units require water injection for NO_x control. Siemens' small industrial gas turbines have extensive H_2 combustion experience, including refinery and coke oven gas with high H_2 contents in conventional burners and H_2 blends in DLE combustors. Their midsize gas turbines have more than 10 years of H_2 combustion experience, drawing from R&D activities and operations with high H_2 refinery fuel gas. Finally, their large gas turbines have more than 45 years of H_2 experience from IGCC projects with up to 60% H_2 tests. The H_2 capabilities that Siemens currently advertises are summarized in Table 3. Siemens also advertises the possibility of augmented H_2 capability on a project by project basis.

Siemens' future H_2 plans as illustrated in their July 2019 Hydrogen Combustion Sales Information brochure [28] are driven by H_2 cofiring in Europe. Siemens is targeting 20% H_2 capability in all models by 2020 (aeroderivative through frame units, with many already at 30%) and 100% H_2 capability in all models by

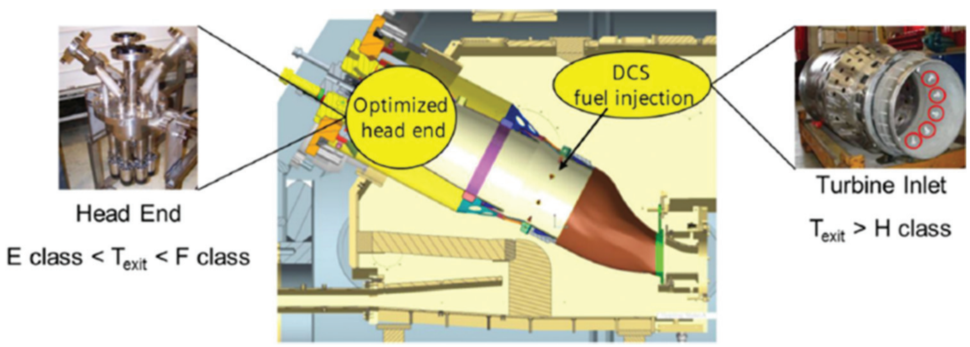


Fig. 7 Siemens distributed combustion system concept, including advanced head end combustor. Figure shows the DCS fuel injection location which is well downstream of the main combustor. Figure reproduced from Ref. [30].

Table 3 Advertised hydrogen capabilities of the Siemens gas turbine fleet [28]

				H_2 capability, Vol %		
		Frequency (Hz)	Power output, MW. Natural gas, ISO base load	DLE	WLE	Diffusion, unabated NO_x
Heavy duty	SGT5-9000HL	50	593	30	—	—
	SGT5-8000H	50	450	30	—	—
	SGT5-4000F	50	329	30	—	—
	SGT5-2000E	50	187	30	—	—
	SGT6-9000HL	60	405	30	—	—
	SGT6-8000H	60	310	30	—	—
	SGT-5000F	60	215–260	30	—	—
	SGT6-2000E	60	117	30	—	—
Industrial	SGT-800	50 or 60	48–57	60	—	—
	SGT-750	50 or 60	40/34–41	40	—	—
	SGT-700	50 or 60	33/34	66	—	—
	SGT-600	50 or 60	24/25	60	—	—
	SGT-400	50 or 60	10–14/11–15	10	—	65
	SGT-300	50 or 60	8/8	30	—	—
	SGT-100	50 or 60	5/6	30	—	65
Aero-derivative	SGT-A65	50 or 60	60–71/58–62	15	100	—
	SGT-A45	50 or 60	41–44	—	100	—
	SGT-A35	50 or 60	27–37/28–38	15	100	—
	SGT-A05	50 or 60	4/6	2	15	—

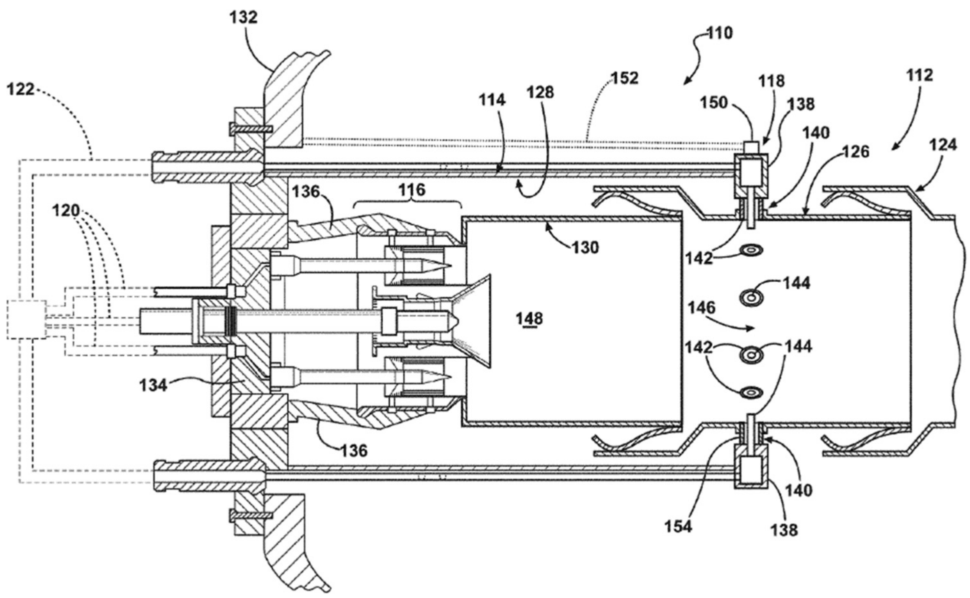


Fig. 8 Siemens combustor assembly drawing, including an axial staging concept. Six staged combustion injectors (numbered 142 and 144) are shown in this section well downstream of the main combustor. Figure is reproduced from Ref. [32].

2030 [29]. Some of these anticipated developments will be implemented in new units and retrofits. For example, the 10 to 30% H_2 range will require combustor upgrades which include modified burners, higher temperature materials, an advanced gas detection system, and leak checks after maintenance. The 50 to 70% range will require new burner designs and bigger fuel pipe diameters and may require start up and shut down on conventional fuels. Siemens' past and future roadmap to 100% H_2 capable low NO_x gas turbines begins with full pressure testing soon after 2019, followed by 100% H_2 capability in aeroderivatives, then industrial gas turbines, and finally heavy-duty gas turbines. The roadmap also identifies future development of the DLE technology for low NOx, high temperature combustion extended to 100% H_2.

The U.S. DOE Office of Scientific and Technical Information has published a final report from Siemens' Advanced Hydrogen Turbine Development program [30]. This program was sponsored by the National Energy Technology Laboratories and overviews several new technologies, including combustion system technologies. Siemens discusses many of the key physics and engineering challenges in this report. For example, the report details the challenge of flashback for H_2 and residence time for NO_x, and the intersection of these challenges with Siemens' ultra low NO_x (ULN) combustion system. The report discusses the development of an advanced ULN head end combustor with modified fuel injectors to combat flashback, and a fuel staging concept which is referred to as the "distributed combustion system (DCS)." The report shows results from university testing, including micromixing nozzles, and full-scale testing with greater than 80% H_2. They also demonstrate NG operation at greater than J class temperatures with reasonable NO_x emissions. The advanced head end combustor and Distributed Combustion System are reproduced from the report in Fig. 7.

Siemens has also released patents that show the DCS concept on their combustors [31] and the associated fuel ducting [32]. Figure 8 presents an example of one of these patents. Like the drawing and photograph of the DCS in Fig. 7, Fig. 8 portrays a secondary fuel injection system downstream of the main combustor. The section view in the patent shows six discrete fuel injection holes, with an assumed ten total injectors for the combustor. The fuel injectors are numbered differently, suggesting a degree of fuel staging (i.e., different distributions of fuel between the staged injectors).

Mitsubishi Heavy Industries (MHI) is currently working to accommodate larger fractions of H_2. Their strategy is a multicluster diffusion burner, consisting of many small diffusion burners. Each nozzle can mix fuel and air. The result is many small nonpremixed (or partially premixed) flames which are robust against flashback, but with rapid air mixing to reduce temperatures and control NO_x emissions. This project is reported to be in early stages. The technology has been tested on small gas turbines and is planned as a retrofit to replace the combustion components (fuel nozzle, combustor basket, transition piece, igniters, and flame detectors). In addition, a fuel line modification will be required to accommodate the higher flow that will be required for high H_2 fuels. To date, the technology has been tested at 30% H_2 in a 1600 °C (J class) DLN combustor. A fuel gas composition with 30% H_2 provides a 10% CO2 reduction relative to pure NG fuel. A 100% H_2 goal is slated for 2030.

Mitsubishi Heavy Industries has published the technical developments that are being incorporated into the multicluster diffusion burner. The burner concept consists of many small, very short premixing passages with rapid mixing to minimize flashback risk. Each burner clusters these passages together so that they inject fuel and air with swirl to induce flow recirculation (see Fig. 9 for an outline of the general concept).

The multicluster diffusion burner is designed to establish a lifted flame at the stagnation point of the recirculation zone. For example, Fig. 10 presents a cartoon of the flame shape for a single burner published by MHI [34]. The lifted flame is key to the low NOx strategy so that the separate fuel and air streams from the cluster can complete mixing upstream of the flame.

Mitsubishi Heavy Industries has released several publications that show multiple fuel stages for this concept, similar to modern day lean premixed systems.

Figure 11 identifies three general fuel stages, including a liquid fuel nozzle, a pilot burner (F1), and main burners. The six main burners are further partition into four additional fuel stages according to Fig. 12. These stages consist of two groups of three outer burners, with each group on a separate fuel stage. The groups are named F2 and F3. Furthermore, each of these groups has an inner fuel stage and an outer fuel stage.

Figure 12 also illustrates the general strategy for fuel stage manipulation during loading. The figure shows oil-only operation on the left, and hints that oil-only operation can access low loads.

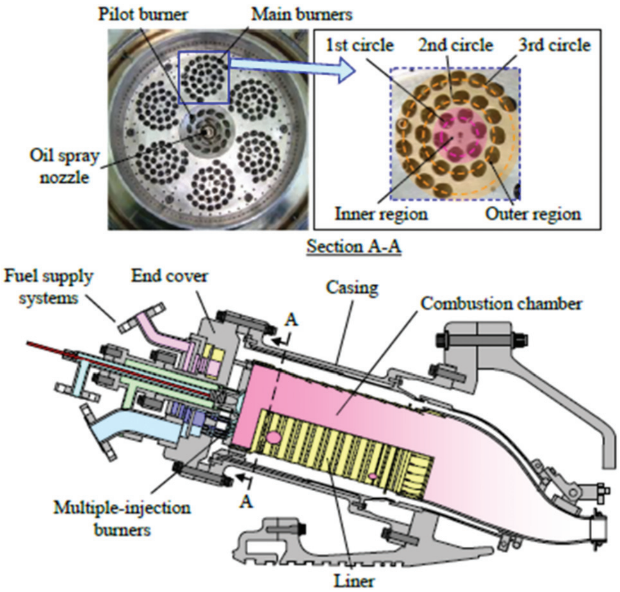


Fig. 9 Conceptual outline of the MHI multicluster diffusion burner, reproduced from Ref. [33]. Figure shows (top-left) full array of burners for a single combustor can, (top-right) arrangement of fuel injectors for a single burner, and (bottom) fitment of the multiple injection burners into the combustor with a partial overlay of the liner.

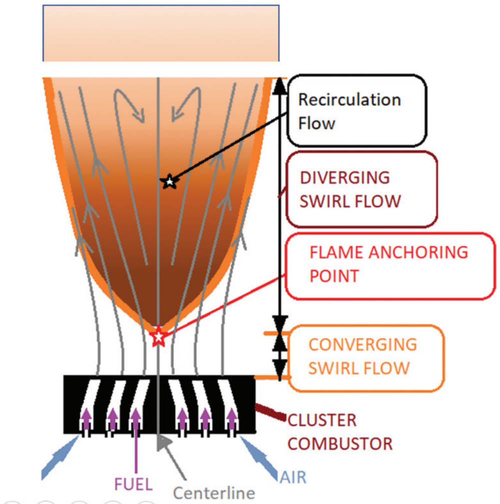


Fig. 10 Illustration of the fluid mechanics and flame configuration in the MHI multicluster diffusion burner, illustrated from Ref. [34]

The figure also shows fueling to the F1 (pilot stage) and F2-1, F3-1 (inner stages) at lower loads with fueling to all stages at high loads. The figure also hints at an "Advanced" versus "Initial" mode. The authors speculate from the figure that the advanced mode uses more outer fuel for better premixing and lower NO_x.

Extensive testing has already been performed on this concept, which demonstrates significant investment in and maturation of the technology. For example, Fig. 13 shows the load and operating mode dependence of emissions and combustion dynamics. The figure suggests that the manufacturer has been successful at mitigating combustion dynamics and limiting NO_x emissions with the available fuel splits. The figure also shows that today's challenges of fuel system tuning to balance emissions and dynamics will likely remain relevant in next generation systems.

In addition to the multicluster diffusion burner, MHI has developed a combustion system for H_2-rich syngas fuels in oxygen-blown IGCC plants [34]. The nozzles in this combustion system somewhat resemble the multicluster diffusion burner. In this case, the concept is a transition from a premixed combustor to a diffusion combustor for flashback prevention, and injection of diluents (water, steam, and/or nitrogen) for NOx abatement.

A recent Turbomachinery International article reports an interview with Ansaldo, where the manufacturer explains that a high H_2 fuel supply will require attention to the fuel skid and controls to avoid leakage and maintain safe operation [35]. Ansaldo discusses the need for rapid mixing to enable high H_2 technology. They describe a strategy for flashback mitigation that requires high premixer exit velocities with appropriate boundary layer control. Furthermore, they discuss the need for a more robust flame stabilization mechanism that can handle changes in flame speed (for example, a stabilization mechanism that does not blow out when H_2 content is reduced). Ansaldo Thomassen's low emission combustion combustor is currently capable of up to 25% H_2. The Power Systems Manufacturing (PSM) Flamesheet^{TM} combustor can handle up to 40% H_2. According to Ansaldo Thomassen CEO

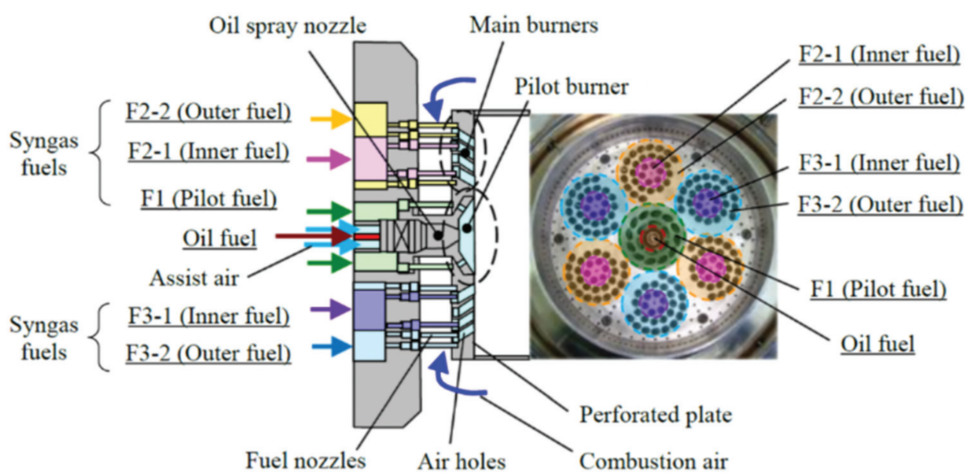


Fig. 11 Main fuel injection staging for the MHI multicluster diffusion burner. The figure is arranged with a side view (left) of the fuel injection system, which shows the various fuel stages that are plumbed to each burner. The right side of the figure shows the burner head-on (i.e., looking upstream) with the fuel stages annotated for reference. Figure is reproduced from Ref. [33].

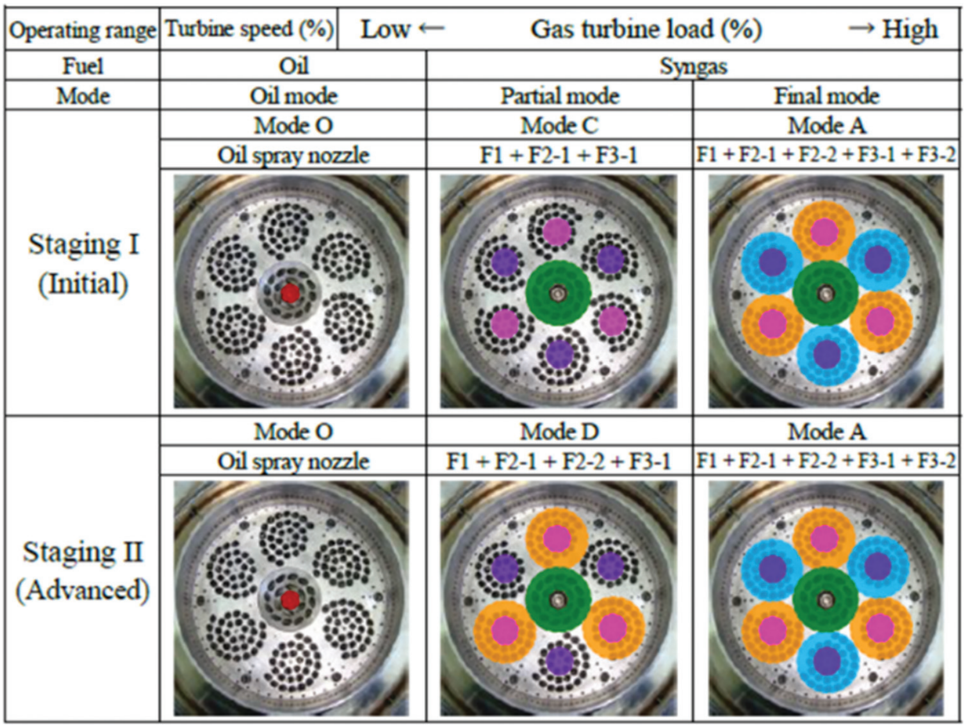
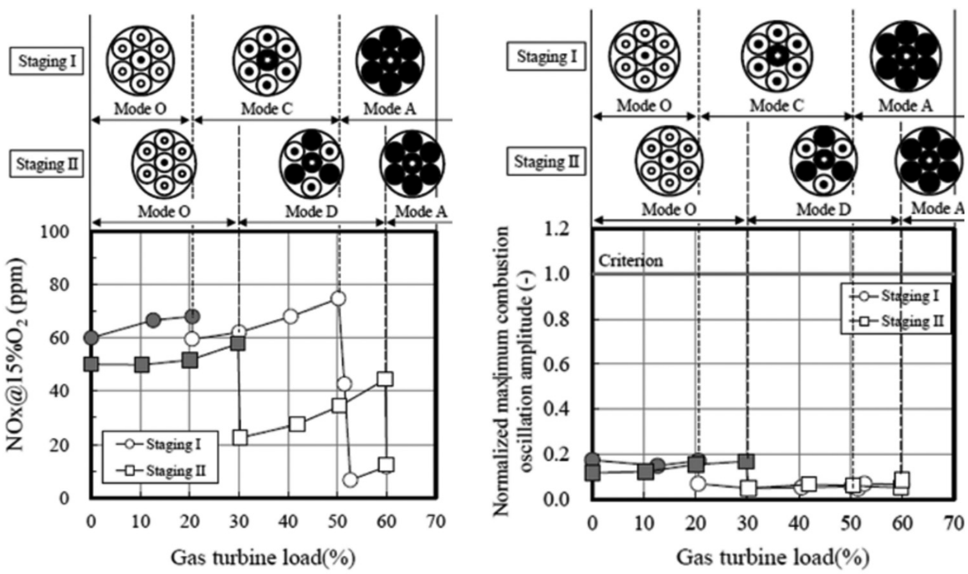


Fig. 12 Firing modes of the MHI multicluster diffusion burner, showing the distribution of fuel between the various fuel stages as load is varied. Figure is reproduced from Ref. [33].

Peter Stuttaford "tests are ongoing to demonstrate 80% H_2 capability for Flamesheet, and development work is ongoing for a 100% H_2 demonstration." Moreover, test data has been published showing various successes for Ansaldo Energia with testing standard GT36 hardware up to 70% H_2 and essentially full range capability is possible with corresponding derates [36].

A recent article from Power Magazine in May of 2019 nicely summarizes the development efforts of the different OEMs to boost H_2 capabilities, with some of the noteworthy efforts expanded here [8]. Mitsubishi Hitachi Power Systems (MHPS), Siemens Energy, and Ansaldo Energia are all working diligently to secure a place in the market with the technologies talked about previously. MHPS has 29 units with H_2 capabilities ranging from 30 to 90% but notes the key challenges of NOx emissions and flashback as the technology evolves. MHPS has several conversion projects in the works. One is in the Netherlands at Nuon's Magnum power plant that will be using a diffusion combustor (CCGT M701F 440 MW) firing 100% H_2 by 2024 [37]. This project is estimated to reduce CO_2 emission by 2 Mt/year. Siemens and Ansaldo have H_2 capabilities noted as well, with both



(*a*) (*b*)

Fig. 13 (*a*) NO_x and (*b*) dynamics test results for the MHI multicluster diffusion burner, showing sensitivity of these phenomena to firing mode (fuel staging). Figure reproduced from Ref. [33].

Table 4 Available OEM capabilities and future plans [11,24,28,38,39]

	Type	Notes	TIT°C (°F) or class	Max H_2% (Vol)
MHPS	Diffusion	N_2 dilution, water/steam Injection	1200–1400 [2192–2552]	100
	Premix (DLN)	Dry	1600 [2912]	30
	Multicluster	Dry/underdevelopment—target 2024	1650 [3002]	100
GE	SN	Single nozzle (standard)	B, E class	90–100
	MNQC	Multinozzle quiet combustor w/ N_2 or steam	E, F class	90–100
	DLN 1	Dry	B, E class	33
	DLN 2.6+	Dry	F, HA class	15
	DLN 2.6e	Micromixer	HA class	50
Siemens	DLE	Dry	E class	30
	DLE	Dry	F class	30
	DLE	Dry	H class	30
	DLE	Dry	HL class	30
Ansaldo	Sequential	GT26	F class	30
	Sequential	GT36	H class	50
	ULE	Current Flamesheet	F, G class	40
	New ULE	Flamesheet—Target 2023	Various	100

focusing on new technologies to reduce emissions levels and push toward 100% H_2 capabilities congruent with NG DLN type technologies. Table 4 outlines the capabilities known to be current as of publication with any future capabilities that are in development.

Concluding Remarks

Decarbonization is happening at different levels throughout the world. Specifically, in the USA, carbon taxes and carbon caps have just been discussions; however, campaigns like that of "beyond coal" have played a major role in fully shuttering coal-fired power plants since 2011 with aims for all units by 2030 [40]. Along with this June 2019 news report, Michael Bloomberg announced a renewed investment of \$500 M USD for "beyond coal," which is setting eyes on preventing new gas plant construction. Thus, having a path for decarbonized gas turbines in the USA is necessary now. Current technologies are available for certain circumstances, but not as a broad solution. Lower percentage H_2 containing fuels will work with most systems; however, high percentage to pure H_2 fuels pose challenges and still need robust, low-NO_x solutions.

Original equipment manufacturers are working in these areas with the help of U.S. DOE funding along with other market drivers. Hydrogen combustion was a big topic at the 2019 ASME Turbo Expo, where top officials from the major OEMs, along with EPRI's Tom Alley, outlined the need for decarbonized fuel use and pushed the GT R&D community to keep working toward solutions for H_2 use. The GT community is well positioned but needs to keep pushing in order to be ready as the H_2 production community continues to increase the availability of the carbon-free fuel. Overall, most DLN/DLE/ULN systems can currently handle approximately 60% or less H_2 with many OEMs having test data pushing to 80 or 90%. Continued development and experience are needed with holistic considerations for other combined cycle systems such as the HRSG around temperatures, purge requirements, and exhaust water content, for example.

Nomenclature

AFS = axial fuel staging
DCS = distributed combustion system
DLE = dry-low emission
DLN = dry-low NO_x
F = flammability limit equivalence ratio
HRSG = heat recovery steam generator
IGCC = integrated gasification combined cycle
LBO = lean blowoff
LHV = lower heating value
MW = megawatt
OEM = original equipment manufacturer
STP = standard temperature and pressure
ULE = ultra-low emission
ULN = ultra low NO_x
WLE = wet-low emission
Φ = equivalence ratio

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