A LITERATURE REVIEW OF HYDROGEN AND NATURAL GAS TURBINES: CURRENT STATE OF THE ART WITH REGARD TO PERFORMANCE AND NO_X CONTROL

WHITE PAPER

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1 INTRODUCTION

In early 2021, the Biden Administration released executive order #14008 (Tackling the Climate Crisis at Home and Abroad), which discussed a completely carbon-free economy by 2050. One focus of this plan is to achieve a completely carbon-free electricity sector by 2035. The U.S. Department of Energy's (DOE) approach to achieving this goal includes engaging in key research and supporting developing technologies that enable hydrogen (H_2) to meet the current and future energy needs of the United States. One of the most important technologies needed to achieve the goal of a hydrogen-based electricity sector is a 100% hydrogen-fueled gas turbine. Various engine manufacturers have been working on accommodating hydrogen-based fuels of various blending levels over the past several years, but much more research and development (R&D) is needed. The purpose of this white paper is to highlight the current state of the art (SOTA) for gas turbine technology with regard to facilitating hydrogen combustion in a reliable and clean manner, as well as to provide an overview of hydrogen as a fuel and various emissions control techniques that are relevant for hydrogen-based fuels. The key benchmarks for success in achieving reliable hydrogen-fueled turbines are a long lifespan and comparable maintenance schedule compared to natural gas turbines, consistent operation, safety (minimize risk of explosions), high efficiency, and low emissions (nitrogen oxide [NO_X]).

2 HYDROGEN VS. NATURAL GAS FUEL PROPERTIES

Natural gas is the standard primary fuel that is used in a majority of gas turbines to this day. As will be covered in later sections, switching to hydrogen requires special considerations to be made within the gas turbine combustor (emphasis on NO_X emissions). Hydrogen differs from natural gas in a few key ways that are relevant to combustion in gas turbines, as outlined below.

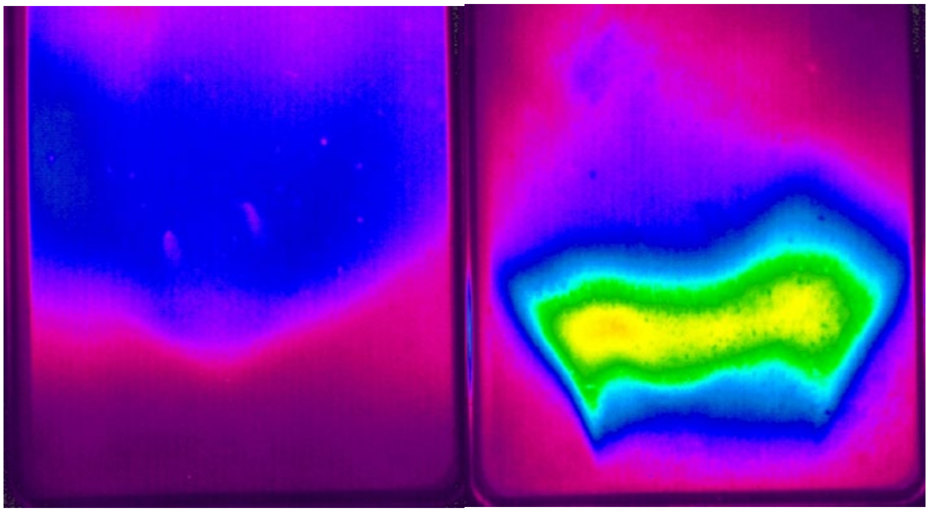
2.1 LOW DENSITY AND ENERGY CONTENT

Hydrogen has the lowest mass density of any substance in the universe, with an atomic weight of only 2.0. It is about eight times lighter than methane (CH_4) [1]. Because of this, there is a common misconception that hydrogen is a superior fuel to natural gas because of its larger heating value (141.86 MJ/kg for H_2 versus 55.53 MJ/kg for pure methane). However, this is due to the fact that hydrogen is *very light* compared to natural gas, not because it actually contains that much energy on a volume basis compared to natural gas. On a molecular basis, there is more energy contained within four C-H bonds compared to one single H-H bond. Also, gas turbine combustors are of fixed volume and designed to work at specific operating pressures with little room for deviation. Therefore, the amount of hydrogen that can be used in a particular gas turbine is limited by volume. Indeed, looking at the energy content on a per-unit-volume or mole basis reveals that natural gas has more than three times the energy density of hydrogen by volume (10,050 kJ/m^3 H_2 versus 32,560 kJ/m^3 CH_4) [1]. Thus, to accommodate hydrogen fuel, hydrogen gas turbines will either need to be larger, incorporate higher max pressures to reduce gas volumes, or both in order to compete with natural gas turbines. This means that, in order to achieve similar performance/emissions ratings to their natural gas counterparts, hydrogen turbines may be more costly to produce.

2.2 HIGH FLAME TEMPERATURE

The adiabatic flame temperature of hydrogen in air is 2,254°C (4,089°F), whereas methane's is only 1,963°C (3,565°F). This has three primary effects that are of concern: (1) increased metal temperatures, which require some form of localized cooling or other technique to protect hot section parts of the turbine from thermal stresses; (2) the potential for higher thermal NO_X emissions; and (3) changes to thermal acoustics (higher temperatures cause changes in thermal loads, causing pressure fluctuations in the combustor, which leads to vibrations that could potentially destroy a gas turbine combustor). Exhibit 2-1 shows chemiluminescence images of natural gas flames both without and with hydrogen. Note the greater chemical activity in the plot on the right, indicative of higher heat generation. The majority hydrogen flame has lower overall luminosity since most of the energy will be released as heat instead of light. Techniques to control the temperature of hydrogen to mitigate these effects are discussed in later sections.

Exhibit 2-1. Chemiluminescence images of flames for natural gas (left) and 80% hydrogen (right)



2.3 HIGH FLAME SPEED

The last major issue of concern with hydrogen as a fuel is its high flame speed. This is perhaps the single most challenging issue to overcome with regard to hydrogen. Compared to natural gas, hydrogen's flame speed is an order of magnitude faster (~3 m/s compared to ~0.3 m/s) than that of natural gas. The high flame speed can also increase local flame temperature (on top of the high natural flame temperature), which exacerbates the issues discussed previously [2]. Nilsson et al. (2017) examined the effects of hydrogen on flame speed for various fuel pre-mixed flames at various fuel-air equivalence ratios (actual fuel-air ratio divided by stoichiometrically complete combustion fuel-air ratio) [3] and found that the flame speed is effectively tripled at hydrogen blends of 70% compared to that of a pure natural gas flame.

Conventional gas turbines make use of velocity-driven diffusion flames or lean-air pre-mixed flames. This means that they are designed with a specific flame speed in mind. If the flame speed is significantly higher than the actual design point fluid velocity, the reaction will propagate backwards ("flashback") into the fuel mixing zone, which can damage the injectors and other components or cause explosions [2-4]. Conversely, a higher fluid velocity can push the reacting species out of the combustor or extinguish the flame completely ("blowout" or "blow-off") [3]. For hydrogen, simply raising the injection velocity is not an option for existing machines because higher velocities will create higher pressure drops across the combustor, which impacts machine work output, efficiency, reliability, maintenance, and life expectancy. Due to the operational limits of gas turbines, newer machines that can handle the higher fluid speeds and balance this with maintaining complete combustion for higher efficiency, keeping NO_X production in check, and having 100% reliable and safe operation, are currently being developed.

3 HYDROGEN COMBUSTION EMISSIONS (NO_X)

As a pure element, hydrogen contains no inherent polluting substances. Thus, aside from pollutants resulting from the combustion of trace substances that may remain after the hydrogen production and purification processes, the only noteworthy pollutant that arises from hydrogen combustion is NO_X. Details on NO_X production are discussed in the following sections.

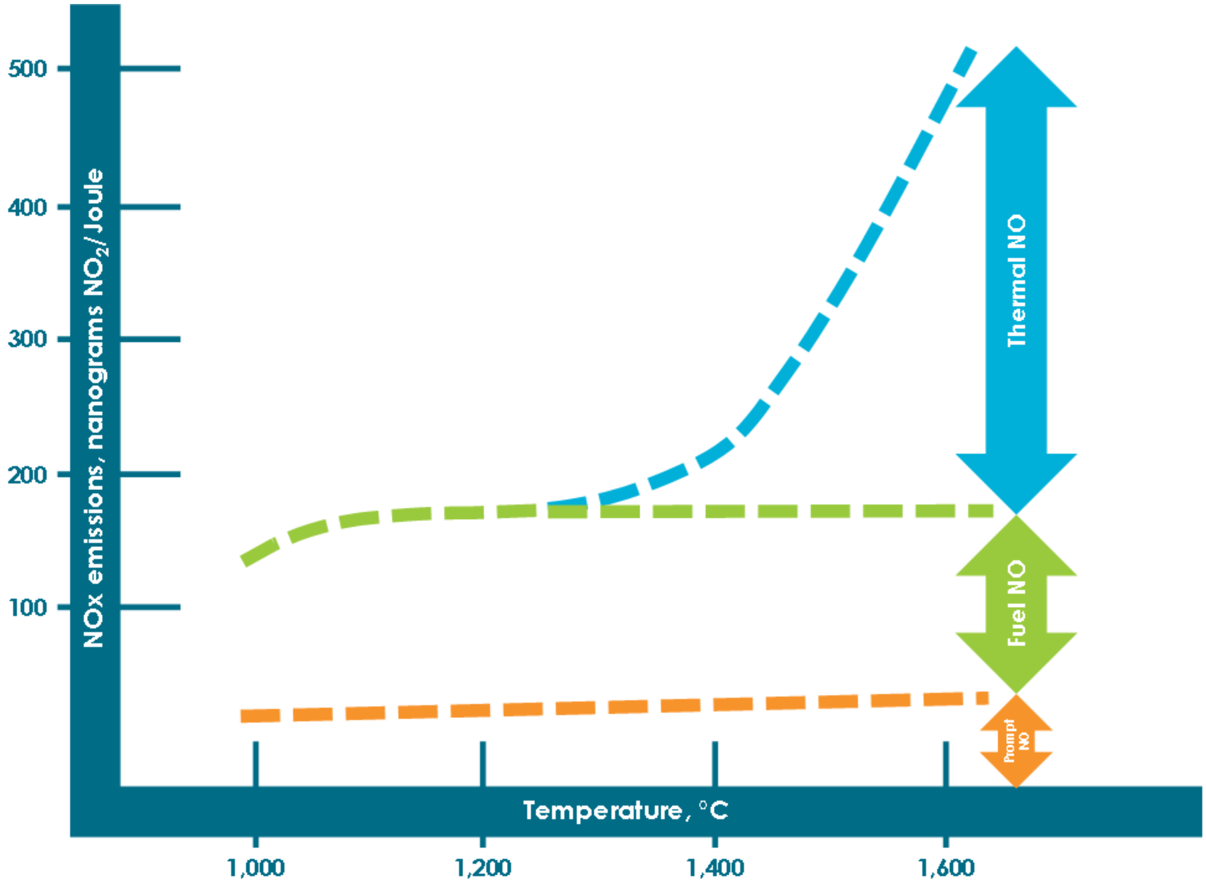
3.1 NO_X FORMATION MECHANISMS

Unlike other pollutants, the actual formation of NO_X is not straightforward, and determining the amount of potential NO_X production from any fuel combustion process requires a precise understanding of the chemical kinetics involved. In total, there are three generalized categories of NO_X: **fuel NO_X, prompt NO_X,** and **thermal NO_X**. Each category has their own independent formation mechanism(s), which are discussed below.

3.1.1 Fuel NO_X

Perhaps the most obvious and intuitive mechanism for NO_X formation is when nitrogen bound to the fuel itself is oxidized directly. The resulting NO_X is called "fuel NO_X," and is only prominent in fuels that have significant nitrogen content (greater than 0.3% N_2). The exact mechanism is not fully understood, but involves the production of nitrous intermediates, such as hydrogen cyanide (HCN) and ammonia (NH_3) due to thermal decomposition, which are then combusted into nitrogen dioxide (NO_2), carbon dioxide (CO_2), and water (H_2O) [5-7]. A common misconception is that fuel and prompt NO_X make up very little of the actual total NO_X, and thermal NO_X is the most prevalent source of NO_X due to the high temperatures associated with combustion. However, in reality, the balance depends greatly on the nitrogen content of the fuel. For most fuels, especially solid fuels, fuel NO_X tends to be the most dominant form of NO_X; thermal NO_X generally does not achieve a clear majority until reaction temperatures of about 1,500°C (2,732°F) are reached, as demonstrated in Exhibit 3-1. In the specific case of hydrogen and natural gas, which generally do not have fuel-bound nitrogen, the aforementioned misconception ends up being true simply due to a lack of available fuel-bound nitrogen as reactant.

Exhibit 3-1. NO$_X$ emissions by category versus temperature (data for biomass combustion)

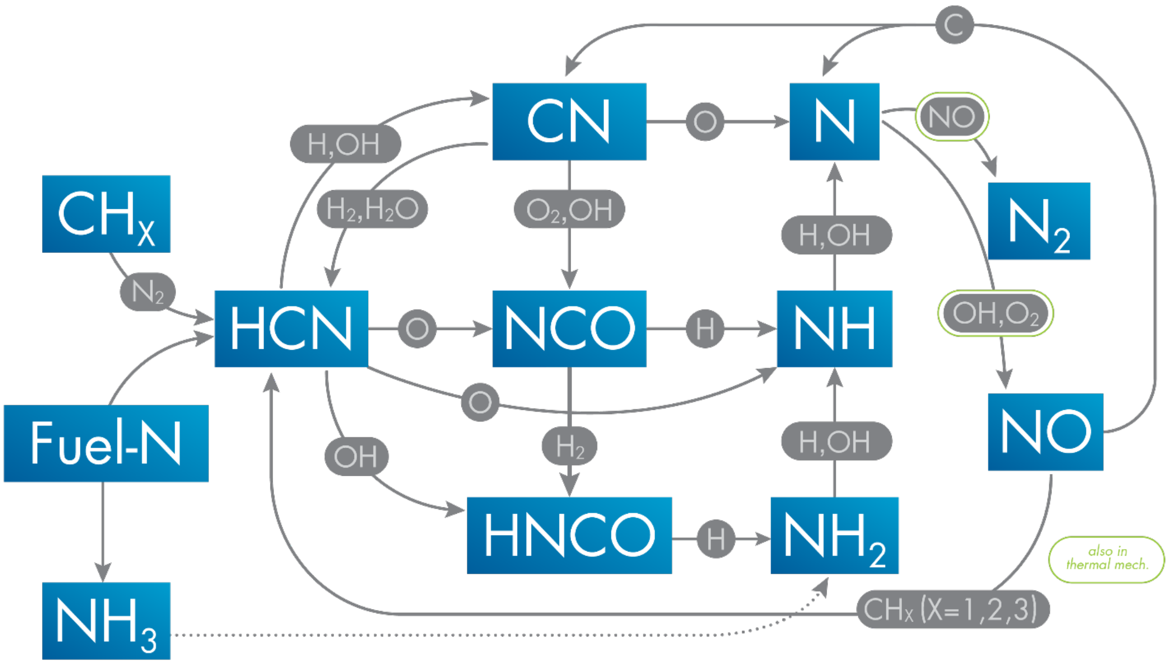


Created based on data from De Nevers [5]

3.1.2 Prompt NO$_X$

Prompt NO$_X$ is typically the least significant type of NO$_X$. For the mechanism, nitrogen in the air reacts directly with the fuel, which creates a cyanide group. Oxygen from the air that combusts the fuel will convert this group into NO$_X$. Prompt NO$_X$ is therefore related to, but not the same as fuel NO$_X$. Oftentimes, the two are analyzed together via a single mechanism, known as the Fenimore mechanism (shown in Exhibit 3-2) [8, 9].

Exhibit 3-2. Prompt and fuel NOx (Fenimore) mechanisms



Based on information from Seitzman [8]

For hydrogen, the NNH mechanism is mostly analogous to the Fenimore mechanism for carbon-based fuels. Similar to the Fenimore mechanism, nitrogen bonds with hydrogen molecules, forming an NNH intermediate ($2N_2 + H_2 \leftrightarrow 2NNH$), which is later combusted to produce NO_X [10]. The word “prompt” refers to the fact that prompt NO_X tends to form during the early stages of combustion and is responsible for the majority of NO_X emissions formed during these early stages, most prominently under low-temperature conditions in particularly fuel-rich flames [6, 11, 12]. Prompt NO_X is mostly unaffected by parameters like residence times [13] and temperature [12], but can be mitigated through fuel-air pre-mixing [12,13].

3.1.3 Thermal NOx

For most high-temperature combustion applications, thermal NO_X is the most prevalent form of NO_X emissions (higher than 1,500°C, as mentioned previously). Thermal NO_X is created by direct oxidation of free nitrogen within the air ($N_2 + O_2 \rightarrow 2NO$). Per its name, thermal NO_X formation rates are a strong function of temperature in addition to residence time and oxygen content [6, 11, 12]. The overall process is described by the Zeldovich mechanism, described by reactions R1–R7 [6, 8, 14]. In regions of the flame where there is a lack of oxygen, nitrous oxide (N_2O) can also be formed from the under-oxidation of nitrogen, as described by reaction R8. Nitrous oxide can also contribute to further nitric oxide (NO) or NO_2 production through reactions with the fuel, but N_2O formation during combustion is generally very rare compared to other NO_X compounds [15], and such intermediate mechanisms are beyond the scope of this paper.

3.1.4 Thermal NOX—The Zeldovich Mechanism

$N_2 \leftrightarrow 2N$ (R1—Dissociation of Nitrogen)

$O_2 \leftrightarrow 2O$ (R2—Dissociation of Oxygen)

$N_2 + O \leftrightarrow NO + N$ (R3—NO_X Formation 1)

$O_2 + N \leftrightarrow NO + O$ (R4—NO_X Formation 2)

$2H_2O + O_2 \leftrightarrow 4OH$ (R5—Hydroxide Formation)

$4H + O_2 \leftrightarrow 2H_2O$ (R6—Reformation of Water)

$N + OH \leftrightarrow NO + H$ (R7—Nitrogen Oxidation via Hydroxide)

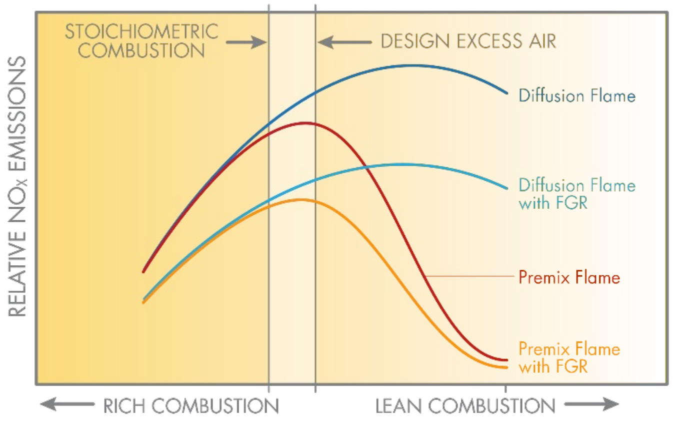
$2N_2 + O_2 \rightarrow 2N_2O$ (R8—Nitrous Oxide Formation)

Here, reactions 3, 4, and 7 are the core of the Zeldovich mechanism [8, 11], while the remaining reactions are necessary to obtain the equilibrium concentrations of key intermediates and complete the mechanism [14].

Thermal NO_X is most easily mitigated by reducing the maximum combustion temperature. Controlled mixing burners, for example, can be used to reduce turbulence in the combustion zone, thus reducing the reaction rate. Pre-mixed combustion allows for a more even distribution of heat energy to keep the maximum temperature lower. Flue/exhaust gas recirculation (FGR/EGR) or similar techniques can dilute the flame itself. Finally, fuel-staged or oxygen-staged combustion can be used to control the fuel-air ratio and different parts of the combustion process, which effectively controls the temperature and limits the amount of NO_X that can be formed when combined with pre-mixed combustion, as shown in Exhibit 3-3.

As Exhibit 3-3 shows, using a pre-mixed flame with either a large amount of excess oxygen or a minimal amount of oxygen limits thermal NO_X production. For high excess air schemes, the low amount of fuel means that less energy is released per unit mass, and it can be absorbed readily by the surrounding gases. For oxygen-poor combustion, lower reaction rates will generate heat more slowly, allowing it to have more time to dissipate, lowering the appearance rate of hot spots. Modern combustors will often use an early fuel-lean pre-mixed flame and a much more fuel-rich flame downstream. Combining the two exhaust streams in a final “burnout zone” further downstream generally results in complete combustion with minimized NO_X [11].

Exhibit 3-3. NO$_X$ emissions for pre-mixed and diffusion flames



Based on data from May [11]

3.1.5 Impact of Hydrogen and Hydrogen/Natural Gas Blends on NO$_X$ in Gas Turbines

In summary, for gaseous fuels with low fuel-bound nitrogen, thermal NO$_X$ is the primary category of NO$_X$ created in gas turbines. For hydrogen specifically, this problem is exacerbated by higher flame speed, which is not only indicative of a higher reaction rate, but it also induces combustion instabilities due to thermoacoustics [16]. As a result, for flames with uncontrolled NO$_X$ emissions, hydrogen is expected to produce more than eight times more NO$_X$ than natural gas under similar conditions [17]. However, for lean pre-mixed flames, these emissions can be mitigated to the point that applicable NO$_X$ control technologies (such as selective catalytic reduction [SCR; see later discussion]) can bring the emissions down to levels compliant with current U.S. Environmental Protection Agency (EPA) regulations, if not comparable to those produced by ordinary natural gas turbines. It is thus predicted that hydrogen gas turbines of the future will be able to compete with current natural gas engines.

3.2 NO$_X$ CONTROL TECHNIQUES

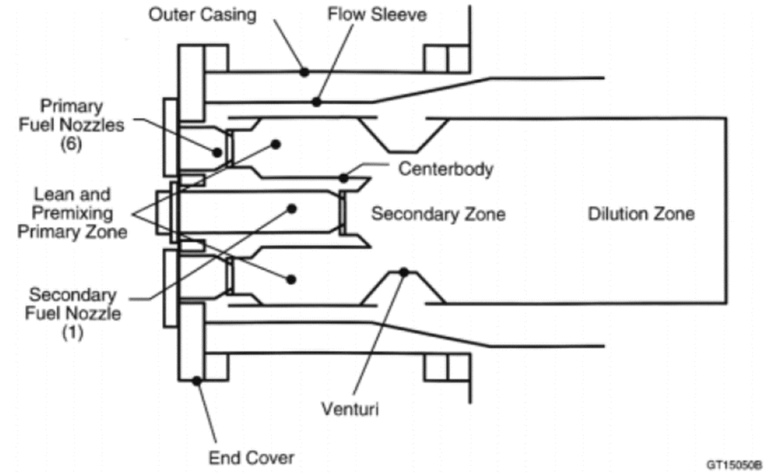
Several modern techniques exist for reducing the amount of NO$_X$ produced by diffusion and premixed flames, and all are applicable to gas turbines. The three most prominent techniques include altering the design of the combustor fuel injection zone, various flame dilution strategies, and post-combustion SCR or selective non-catalytic reduction (SNCR). One strategy that has seen great success with Rankine cycle plants (coal- and natural gas-fired) is oxy-fuel combustion, where air separation is used to create nearly 100% pure oxygen to perform the combustion, eliminating thermal NO$_X$ completely. This strategy, however, is much more complex and costly for gas turbines, and, though there is a growing body of research on this technique, it is not currently actively practiced in industry [18-20].

3.2.1 Low-NO$_X$ Combustor Geometry and Fuel Injection Strategies

The most widely implemented technology to control NO$_X$ involves specific combustor designs that facilitate specific thermo-fluid behavior in order to limit NO$_X$ production. Hydrogen cost and the difficulty of developing these combustors is a primary reason why pure hydrogen-fueled turbines have not fully entered mainstream use, as the differences between hydrogen and natural gas as fuels, as mentioned previously, mean that the same combustor design may not necessarily be able to handle hydrogen in the same way it can accommodate natural gas.

Exhibit 3-4 shows a simplified representation of a dry, low-NO_X (DLN) combustion chamber. The primary injection region occurs on the sides of the chamber. In this region, about 83% of the fuel is combusted under oxygen-lean conditions. The central tube, meanwhile, will handle about 17% of the fuel under highly oxygen-rich conditions. As discussed earlier, both fuel schemes lead to reduced NO_X formation compared to stoichiometric conditions. The two streams mix together in the downstream dilution zone, where the remaining air from the central injector completes the overall combustion process [21].

Exhibit 3-4. Simplified diagram of an early low-NO_X combustion module



Used with Permission from GE Gas Power [21]

To accommodate hydrogen in the fuels, the geometry of these combustors will need to be reworked to accommodate hydrogen's high flame speed and reactivity. In addition, injection nozzle diameters may need to be widened to allow more fuel into the chamber to ensure similar total fuel energy input rates. Overcoming these challenges continues to be an important point of research, as gas turbines are highly integrated machines, and changes in the combustor geometry can affect performance and operation in other areas (i.e., the compressor and turbine sections) as well.

3.2.2 Flame Dilution

In the case that a given combustor design is not sufficient to meet local NO_X emissions targets, a strategy to employ is using another gas to dilute the flame. One technique that takes this approach is to directly inject an external fluid into the gas turbine combustor, which will usually be water/steam or nitrogen (CO_2 can also be used). In this case, the flame is directly quenched to provide a heat sink to lower local temperatures and reduce thermal NO_X formation. In addition, due to the extra mass present, the turbine section of the gas turbine will produce higher gross power at the same expansion ratio. However, the additional parasitic work to compress the injected fluid(s) offsets this, so the effect on net power/efficiency varies case-by-case. In the case of Integrated Gasification Combined Cycles (IGCCs), large-scale plants will often make use of an air separation unit (ASU) to generate oxygen for the gasifier. In cases like this, the extra parasitic loads for making use of leftover nitrogen for diluting the gas turbine combustor flame is minimal compared to the increased turbine power, thus improving the efficiency.

For water/steam, it can be injected as either a gas or as atomized water droplets. Water injection has the greatest NO_X reduction potential due to lower liquid temperatures and latent heat. However, it is important to remember that this particular technique, as well as the previously mentioned staged combustion technique, only affects thermal NO_X formation, and water/steam injection in particular may actually *increase* the rate of fuel NO_X formation depending on the situation [22]. As always, careful experimentation/testing is required to optimize turbine/cycle performance and NO_X emissions of any particular engine and/or cycle.

Alternatively, *flue gas recirculation (FGR, sometimes called exhaust gas recirculation or EGR)* can be used to reduce the combustor peak temperature. With FGR, about 30–50% of the outgoing flue gas is fed back into the gas turbine compressor intake, which not only dilutes the flame, but also has the added benefit of raising the CO_2 concentration in the exhaust. This raises the capture efficiency of CO_2 capture units downstream in the event that they are needed to achieve CO_2 target emissions [23,24]. For combined cycle power plants, FGR can boost the efficiency of the plant by lowering the demand for recycled steam for a carbon capture unit's reboiler [25], but also affects the stability of the flame [26].

3.2.3 Selective Catalytic and Non-Catalytic Reduction

In the rare event that no combination of the previously mentioned techniques can achieve the proper NO_X emission targets, a potential last resort is the use of SCR or SNCR technology. Both techniques involve the injection of a reagent, which will usually be either ammonia or urea, into the post-turbine flue gas. The only difference is that, per its name, SCR makes use of a catalyst to increase the reaction rate and lower the NO_X concentration equilibrium point, while SNCR does not. However, each method has different temperature requirements and follows a different injection scheme to maximize effectiveness, with SNCR generally requiring higher temperatures due to the absence of a catalyst [25]. The general chemical reaction scheme governing these processes is given by reactions R8–R10.

3.2.3.1 Selective Catalytic and Non-Catalytic Reduction Reactions

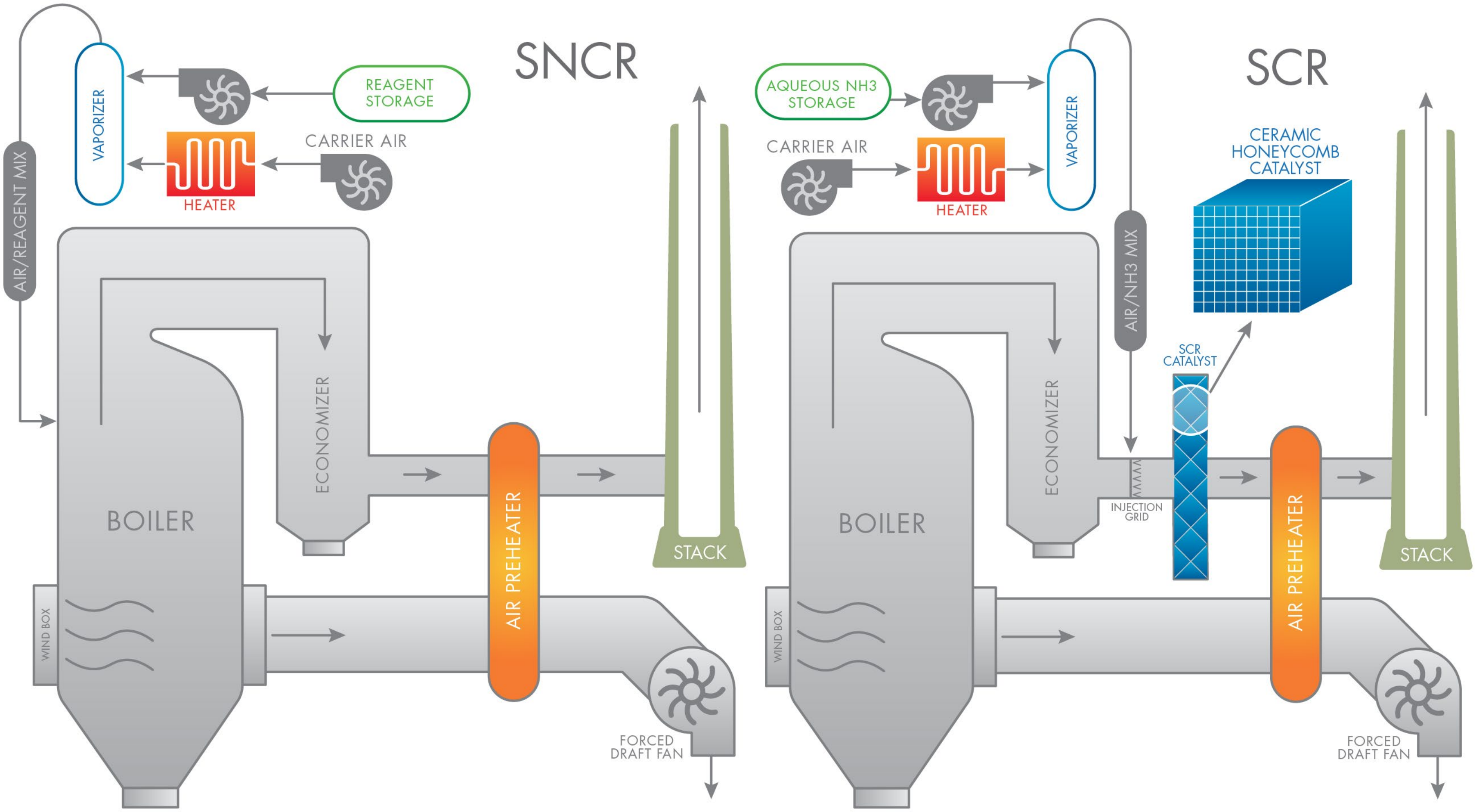
$$4NO + 2(NH_2)_2CO + O_2 \rightarrow 4N_2 + 2CO_2 + 4H_2O \qquad \text{(R8—Reduction via Urea)}$$

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \qquad \text{(R9—Reduction via Ammonia 1)}$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \qquad \text{(R10—Reduction via Ammonia 2)}$$

Typical catalysts used for SCR include titanium dioxide (TiO_2) and vanadium-5 oxide (V_2O_5); however, other catalysts like other base metal oxides, precious metal oxides, or activated carbon have been used [26]. A general simplified diagram of both technologies in coal boiler systems is shown in Exhibit 3-5 for comparison.

Exhibit 3-5. SNCR (left) versus SCR (right) as used in Rankine cycle boilers



Based on info from Bell and Buckingham [25]

In Exhibit 3-5, note the honeycomb catalyst grid put in place for SCR that is absent for the SNCR scheme. A rough summary of the performance and costs of both technologies can be reviewed in Exhibit 3-6. In general, SNCR is much cheaper to implement than SCR due to the lack of catalyst, but requires higher temperatures to be effective, is less effective in flue gas with lower existing NO_X concentrations, and has more variability in how much NO_X can be eliminated (and even then, it cannot reach the reduction levels possible with SCR) [27]. Typical SNCR reduction of NO_X is 40–60% on average, but removal rates as low as 25% or as high as 85% have been reported, depending on application and reagent choice.

It should also be noted that SNCR is not typically suitable for gas turbines for these reasons, but is included here for completeness. Gas turbines, through the use of the two previously mentioned techniques, have low NO_X concentrations in the flue gas and low flue gas temperatures (900–1,200°F depending on frame type). It is preferrable to have temperatures in the 1,500–1,950°F range and with NO_X concentrations more than 200 parts per million (ppm) to maximize the effectiveness of SNCR [28].

Exhibit 3-6. SCR versus SNCR (costs in 2003 USD) **[25]**

Control Technology	Application	NO_X Reduction (%)	Capital Cost	
			($/Ton)	($/kW)
SNCR	Boilers/Process Heaters	40–60	500–1,000	10–20
SCR	Boilers/Process Heaters	80–90	1,000–10,000	20–200

One last point of consideration for SCR/SNCR is ammonia slip, where unreacted ammonia will find its way into the flue gas. Ammonia is itself an unregulated pollutant, but typical ammonia slip levels will be on the order of 2–10 ppm, which are not significant enough to affect plume formation or present a human health hazard [29]. The primary issues with ammonia slip are the formation of ammonia salts, which can deposit on and corrode downstream components and ductwork, and the deposition of ammonia into ash particles (solid fuels only), which can affect ash disposal and reuse. Two primary salts that can form from ammonia slip are ammonium sulfate [$(NH_4)_2SO_4$] and ammonium nitrate (NH_4NO_3). Ammonium sulfate is only a primary concern for fuels with high sulfur content, but ammonium nitrate will readily form when excess ammonia reacts with NO_X. Both salts form more readily when high amounts of sulfur oxides (SO_X) and water occur in the flue gas, which deactivate catalyst reaction sites [29]. In addition, both salts are contributors to secondary particulate matter (PM) emissions, particularly those less than 2.5 microns in size (PM2.5) [30, 31]. A competing technology, called the SCONOx™ process, removes both carbon monoxide (CO) and NO_X from flue gas via a platinum catalyst and potassium carbonate adsorbent, with no ammonia required. However, SCONOx requires a dilute H_2 and CO_2 gas to remove the captured NO_X from the adsorbent to regenerate it. In addition, a number of practical issues with SCONOx have limited its market penetration, including a high exhaust gas pressure drop, safety and reliability issues, and high capital costs [31].

4 CURRENT STATUS OF OEM HYDROGEN AND NO$_X$ CONTROL

Most major turbine engine manufacturers have made substantial progress in both low-NO$_X$ designs and directly implementing hydrogen into their accepted fuel profiles. A significant amount of research into hydrogen combustion in turbines, boilers, and other engines/reactors has been performed for many decades. The following sections will focus on General Electric (GE), Siemens, and Mitsubishi Heavy Industries (MHI; now a part of Mitsubishi-Hitachi), which are the three largest turbine manufacturers in the world in terms of market share. Other manufacturers' research progress and state-of-the-art turbines will be collectively discussed in a separate section. Exhibit 4-1 offers a brief summary of several commercial technologies produced by these three original equipment manufacturers (OEMs) that allow gas turbines to achieve some level of commercially viable hydrogen combustion [32].

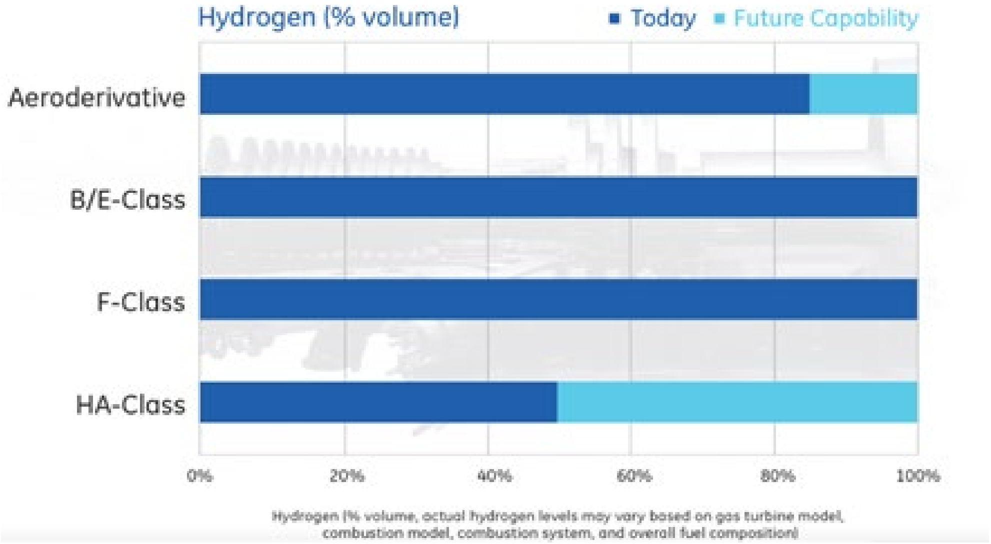
Exhibit 4-1. Hydrogen combustion technologies from the three largest OEMs as of 2019 **[32]**

OEM	Type	TIT or Frame Type	H_2 (vol%)	Notes
MHI	**Diffusion**	1,200–1,400°C (2,192–2,552°F)	Up to 100%	N_2/Water/Steam Injection
	Pre-Mixed (DLN)	1,600°C (2,912°F)	Up to ~30%	Dry
	Multi-Cluster	1,650°C (3,002°F)	Up to 100%	Dry—Under Development (2024)
GE	**DLE**	—	Up to 5%	Aeroderivative—Dry, Low Emissions
	SAC	—	30-85%	Aeroderivative—Singular Annular Combustor
	SN	B/E	90–100%	Single Nozzle (Standard)
	MNQC	E/F	90–100%	Multi-Nozzle Quiet Combustor (w/N_2 or Steam)
	DLN 1	B/E	Up to ~33%	Dry, Low-NO$_X$ 1
	DLN 2.6+	F/H	Up to ~15%	Dry, Low-NO$_X$ 2.6
	DLN 2.6e	9HA	Up to 50%	Dry, Low-NO$_X$ 2.6 "Evolution" (to be implemented in other models)
Siemens	**DLE**	—	2–15%	Aeroderivative
	WLE	—	15–100%	Aeroderivative—Wet, Low-NO$_X$
	DLE	E/F/H	Up to 30%	—
	Diffusion	E/F/H	Up to 100%	No NO$_X$ Abatement
	DLE	HL	Up to 30%	—

4.1 GENERAL ELECTRIC

GE Gas Power ("GE") is the single largest manufacturer of gas turbines in the world by market share as of this writing, and has been a leading pioneer in hydrogen turbine R&D for more than 30 years, now having more than 75 current turbine models able to run on hydrogen-based fuels. GE's most recent commercial combustor design—the DLN 2.6e—uses an advanced pre-mixer technology developed in part through DOE's High Hydrogen Turbine Program [33]. The DLN 2.6e uses miniaturized tubes to increase the speed that pre-mixing occurs. This allows high reactivity fuels, like hydrogen, to be pre-mixed safely and reduces the risk of premature combustion. An overview of current GE engine hydrogen tolerances is summarized in Exhibit 4-2.

Exhibit 4-2. Current status of hydrogen capabilities of GE turbines (vol%)



Used with Permission from GE Gas Power [34]

With regard to NO_X emissions reduction, GE has also led several development efforts for both traditional methods of reduction and DLN combustors. GE-developed DLN combustion systems have been used in more than 200 different engines, including retrofits of older machines [21]. A comparison of select GE engines and relevant NO_X and CO emissions is shown in Exhibit 4-3 [34]. GE engines with DLN technology were some of the first machines to achieve single-digit ppm NO_X emissions in the early 1990s, as shown in Exhibit 4-3. Many newer engines, thanks to improved DLN technology, can reach NO_X concentrations as low as 5 ppm [35]. As of 2019, GE's DLN 2.6e has operated for more than 70 million hours and has successfully been implemented in both F- and H-class turbines [36].

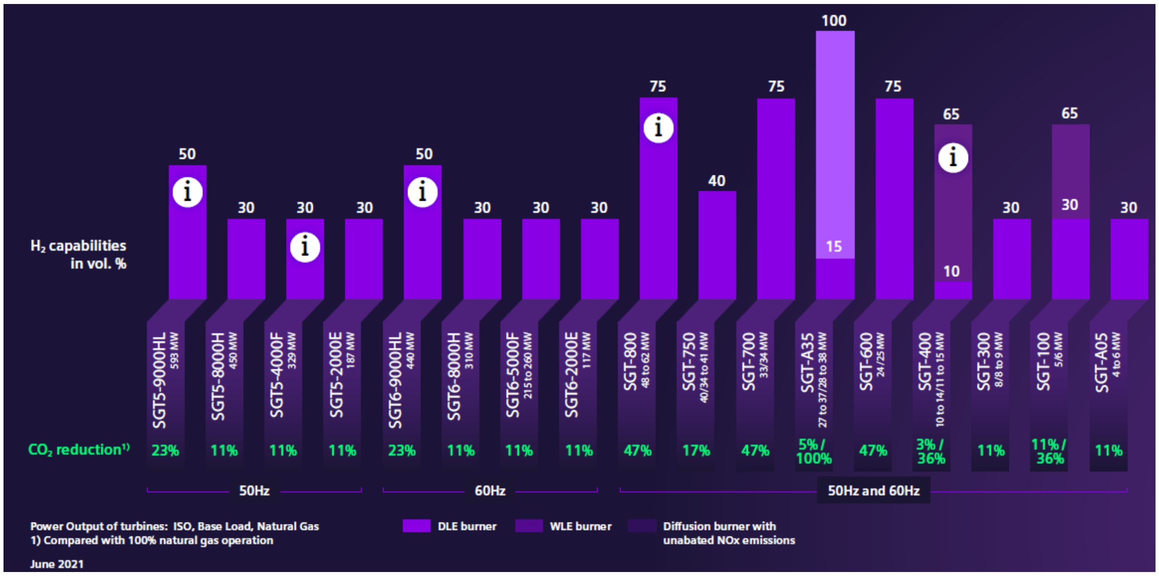
Exhibit 4-3. A comparison of NO$_X$ and CO emissions for various GE turbine engines for natural gas and distillate oil fuels [21]

Turbine Model	Gas			Distillate		
	NO$_X$ (ppmvd)	CO (ppmvd)	Diluent	NO$_X$ (ppmvd)	CO (ppmd)	Diluent
MS3002(J)-RC	33	25	Dry	N/A	N/A	N/A
MS3002(J)-SC	42	50	Dry	N/A	N/A	N/A
MS5001P	25	50	Dry	65	20	Water
MS5001R	42	50	Dry	65	20	Water
MS5002C	42	50	Dry	65	20	Water
MS6001B	9	25	Dry	42	30	Water
MS7001B/E Conv.	25	25	Dry	42	30	Water
MS7001EA	9	25	Dry	42	30	Water
MS9001E	15	25	Dry	42	20	Water
	25	25	Dry	90	20	Dry
MS6001FA	25	15	Dry	42/65	20	Water/Stream
MS7001FA	25	15	Dry	42/65	20	Water/Stream
	9	9	Dry	42/65	30	Water/Stream
MS7001FB	25	15	Dry	42	20	Water
MS7001H	9	9	Dry	42/65	30	Water/Stream
MS9001EC	25	15	Dry	42/65	20	Water/Stream
MS9001FA	25	15	Dry	42/65	20	Water
MS9001FB	25	15	Dry	42	20	Water
MS9001H	25	15	Dry	42	20	Water

4.2 SIEMENS

Siemens Energy ("Siemens") has also made substantial progress in incorporating hydrogen fuels into their turbines. On average, Siemens engines can handle about 30% hydrogen in the gas turbine fuel, with industrial gas turbines capable of up to 60% hydrogen. Siemens offers a control and hardware upgrade package called "H_2DeCarb" to enable E- and F-class turbines to combust larger quantities of hydrogen (typically 50–60%), and Siemens aeroderivative engines have been able to combust 100% hydrogen safely for many years using wet, low-emissions (WLE) combustors that use water injection to reduce NO$_X$ [35]. A chart of select Siemens turbines' hydrogen capabilities is shown in Exhibit 4-4. As of 2019, Siemens also achieved a research breakthrough (still proprietary) that allows hydrogen-tolerant turbine parts to be integrated into existing structures with no welds, significantly reducing construction times [37].

Exhibit 4-4. Hydrogen capabilities of select Siemens gas turbines



Used with permission from Siemens Energy [38]

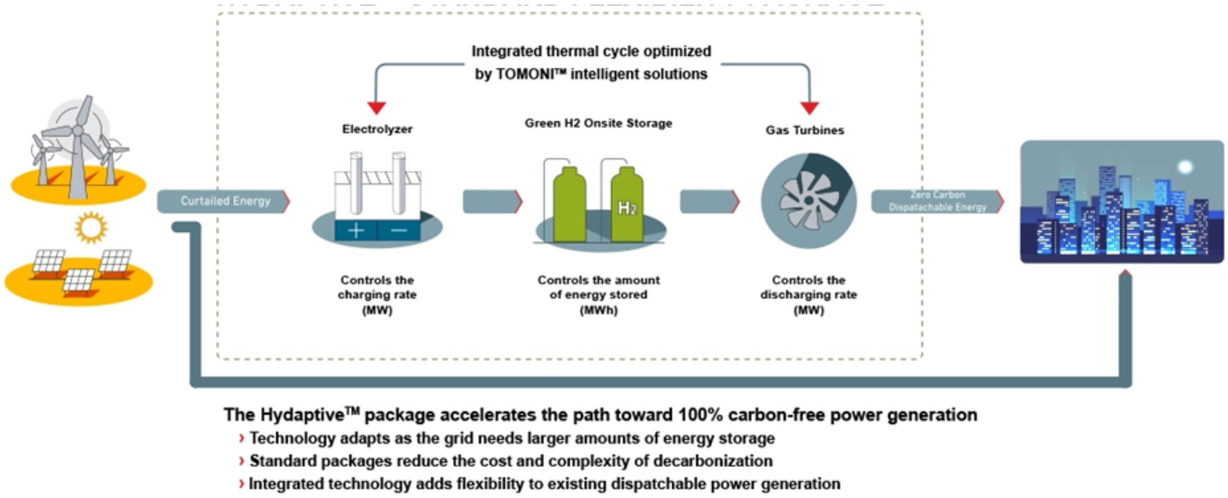
Siemens has been researching and expanding the use of hydrogen in its gas turbines since the 1960s [39], and, along with the rest of the European Association of Gas and Steam Turbine Manufacturers (EUTurbines), is progressing research with the goal of developing a full fleet of 100% hydrogen industrial gas turbines by 2030 [40], the first of which, using DLE combustors for NOx control, is planned to be completed by 2023 [39]. However, as mentioned previously, hydrogen's high flame temperature and flame speed remain key challenges that Siemens, GE, and all other manufacturers continue to face to realize a fully decarbonized gas turbine industry. Yet, as with GE, and as noted earlier, some aeroderivative turbines are already capable of 100% hydrogen. But to keep NOx emissions low (around 25 ppm), which will be a key factor in the environmental success of hydrogen combustion turbines, the WLE combustors require about 20 metric tons, or 20,000 liters, of water every hour. This is also compounded by the fact that the water needs to be demineralized, further increasing operating costs [39].

Siemens' biggest contribution to a global zero-emissions electricity economy so far is the development of a zero-emissions test facility/demonstration plant in Finspång, Sweden, in collaboration with the Zero-Emissions Hydrogen Turbine Center (ZEHTC). The project will demonstrate zero-carbon electricity generated by green hydrogen. The hydrogen will be created via electrolysis powered by excess electricity from nearby prototype turbine testing and solar electrolysis [39, 40]. As of June 2021, all components of the demonstration plant are in place, and operation has begun [40]. Project partners include the Chalmers University of Technology, the University of Bologna, and Linde [39].

4.3 MITSUBISHI HEAVY INDUSTRIES

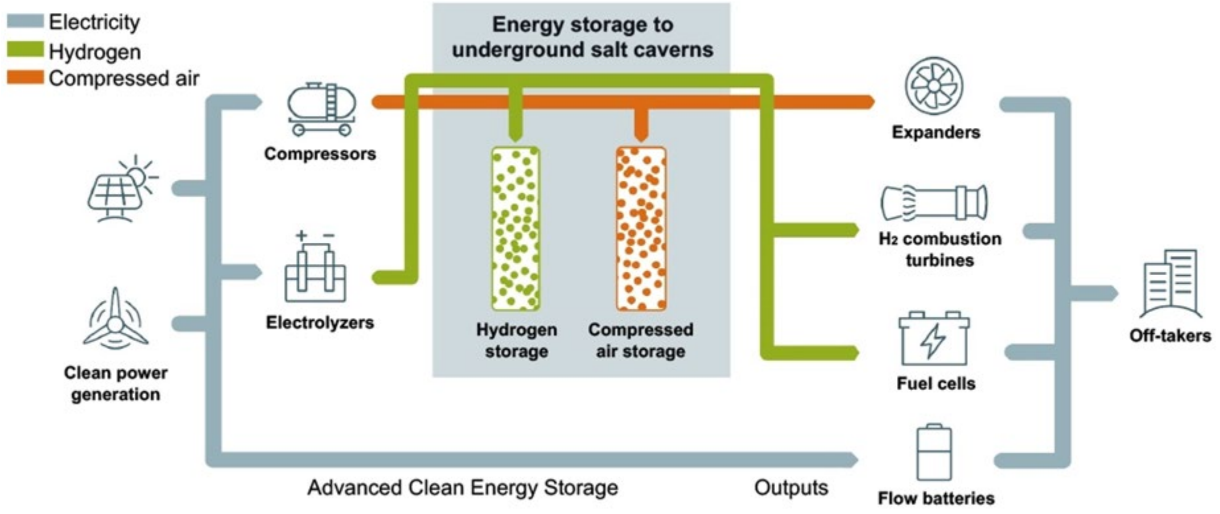
Finally, MHI, which became a part of Mitsubishi-Hitachi Power Systems (MHPS) after a merger with Hitachi in 2014, has also been making progress on developing hydrogen turbines and supporting infrastructure. In late October 2020, then-Japanese Prime Minister Yoshihide Suga declared that Japan will become a decarbonized nation by 2050, echoing previously announced plans from the European Union and the United States. Up to this point, MHI has already succeeded in developing a 30% hydrogen co-combustion engine, and is anticipating a 100% hydrogen engine by 2025 [41, 42]. While the smallest of the "Big Three," MHI has nonetheless achieved numerous advances in gas turbine technology in the past, including the development of the world's first (and, as of this writing, the *only*) J-Class gas turbines (the M501J and M701J-series), boasting turbine inlet temperatures of 1,600°C (2,912°F), more than 100°C higher than equivalent engines from its competitors at the time [43]. For hydrogen deployment specifically, MHI is developing a green hydrogen energy solutions package called Hydaptive^{TM}, which aims to act as a "near-instantaneous" power balancing resource that allows gas turbine power cycles to ramp up and down more rapidly through integration of both hydrogen and natural gas plants. Hydaptive also includes a storage paradigm called "Hystore" [41, 44] to provide off-site hydrogen production and storage infrastructure to maintain a steady supply of hydrogen during peak performance hours. Hydaptive and Hystore are being used in multiple projects throughout the United States (mostly in Appalachia) and Europe, including the Advanced Clean Energy Systems Project, which is co-developed by Magnum Deployment, and uses wind and solar power to produce green hydrogen that is then stored in an underground salt dome [41]. This makes Hydaptive and Hystore the world's first commercially available hydrogen infrastructure and supply packages. Exhibit 4-5 shows a basic schematic of an integrated thermal cycle using the Hydaptive system, while Exhibit 4-6 shows more specific details of the Hydaptive storage package.

Exhibit 4-5. Hydaptive hydrogen power generation system



Used with permission from MHI [41]

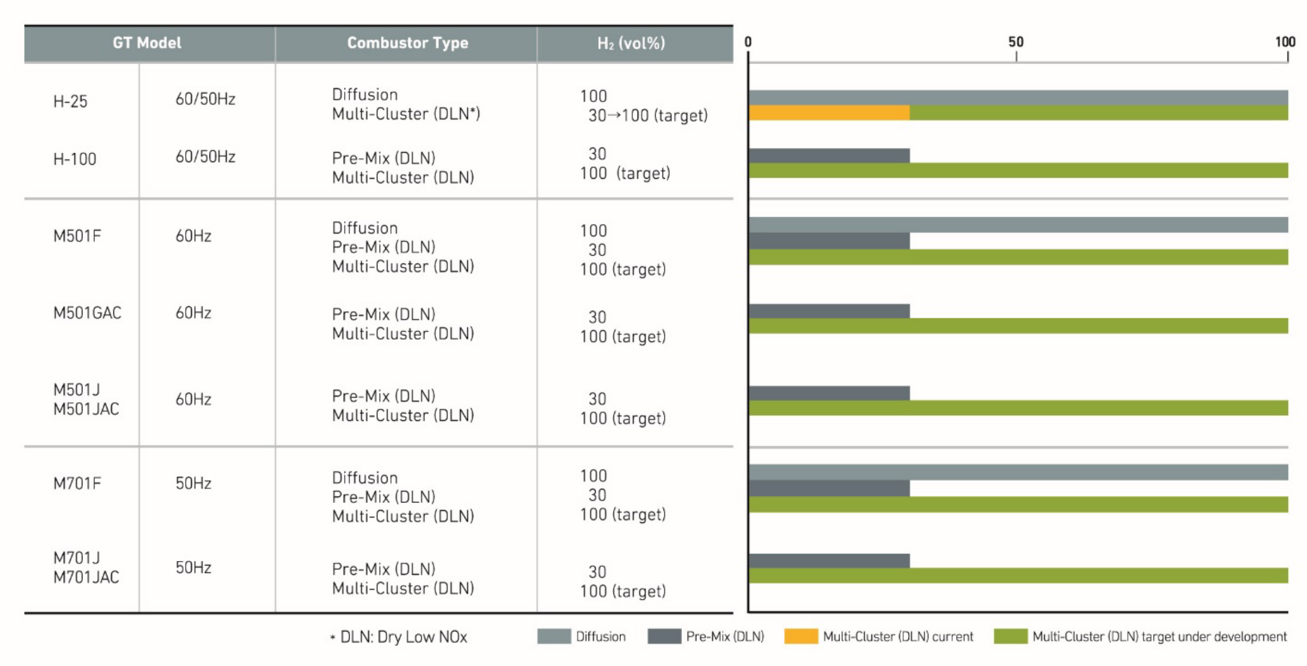
Exhibit 4-6. Close-up of Hydaptive dynamic hydrogen and compressed air storage system



Used with permission from MHI [41]

With unmitigated NO_X, many pure diffusion turbine combustors from MHI are compatible with 100% hydrogen. In order for the operation of these turbines to be practical, innovative NO_X control technologies must be developed. With this limitation in mind, the majority of MHI's current fleet of turbines can operate safely with 30% hydrogen in the fuel, as shown in Exhibit 4-7. To achieve 100% hydrogen capability in all of its turbines, MHI has been developing a unique "multi-cluster" turbine combustor, which is slated to be deployed by 2024 [45]. The combustor makes use of multiple small air and fuel nozzles arranged coaxially, which create a fuel-lean mixture in a much shorter period of time than conventional combustors. Secondly, the combustor design allows for "flame lifting," where the flame forms a distance away from the actual burner, preventing flashback, through directional adjustment of the air jets. The technology has been in development since 2008, and has achieved success at lab-scale and was successfully tested in an H-class machine [46].

Exhibit 4-7. Select MHI gas turbine hydrogen capabilities



GT Model		Combustor Type	H_2 (vol%)
H-25	60/50Hz	Diffusion Multi-Cluster (DLN*)	100 30→100 (target)
H-100	60/50Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M501F	60Hz	Diffusion Pre-Mix (DLN) Multi-Cluster (DLN)	100 30 100 (target)
M501GAC	60Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M501J M501JAC	60Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M701F	50Hz	Diffusion Pre-Mix (DLN) Multi-Cluster (DLN)	100 30 100 (target)
M701J M701JAC	50Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)

* DLN: Dry Low NOx

Used with permission from MHI [45]

4.4 OTHERS

Many other smaller gas turbine OEMs have also made contributions to hydrogen and NO$_X$ reduction research and have also worked to increase the tolerable levels of acceptable hydrogen fuel in their machines. Outside of the "Big Three," the largest manufacturer by market share as of this writing is Solar Turbines ("Solar") [47], mostly due to the recently increased interest in renewable power. In the past decade, Solar's Titan and Taurus engines have been operating on coke oven gas (COG), a typical waste gas created as a byproduct during the creation of petcoke for steel production. COG will typically have between 55–60% hydrogen by volume. Most of these turbines are used in China, where they have operated for more than 1.4 million hours cumulatively. Solar's SoLoNO$_x$™ branding of DLN combustors are comfortably able to operate with up to 20% hydrogen without significant modification [33], and are able to achieve NO$_X$ emissions of 25 ppm (42 ppm on smaller machines) [48]. Solar also participated in a DOE-funded project in collaboration with Precision Combustion Inc., which aimed to develop a full-scale rich catalytic hydrogen injector (RHCI). The results confirmed that the technology was able to achieve low single-digit NO$_X$ emissions with a mixture of 42% hydrogen (remainder being nitrogen diluent) [49]. Solar was also recently selected for a research grant under DOE Funding Opportunity Announcement (FOA) 2400 [50].

Rolls-Royce Power Systems has also started moving forward in decarbonizing its products and operations, including gas turbines. In 2015, Rolls-Royce launched the Green and High-Tech Program, with the goal of creating new mobile engines and engaging in hydrogen testing. The aim of the program is to reduce pollutant emissions and materials consumption throughout the stationary turbine and marine energy market [51]. While specific data on Rolls-Royce turbine hydrogen capabilities could not be found in the literature, the company spent $2.1 billion USD in R&D (with international government support) on the advancement of relevant hydrogen technologies with the goal of completely decarbonizing all of their products and business operations (including turbines) by 2050 [52].

Ansaldo Energia is a smaller manufacturer that offers hydrogen turbines capable of burning fuel with around 25–50% hydrogen content. Internal testing confirmed that Ansaldo's engines can generally handle 30% hydrogen content without modification, with one particular engine having been demonstrated operating with up to 70% hydrogen in the fuel. Ansaldo offers a retrofitted "flamesheet combustor" developed as a commercial solution for E- and F-class gas turbines, allowing up to 40% hydrogen to be used. Several GE engines have already made use of this technology, and it is a simple retrofit to apply to other GE, Siemens, and MHI engines [33].

Baker Hughes is another smaller manufacturer that experienced significant growth in 2019 after it was spun off from GE. Baker Hughes generally specializes in smaller turbines (40 megawatts [MW] or less), but has developed several light industrial-scale turbines in the 100-MW range. From the technology rights inherited from GE, as well as through continued R&D, turbines from this manufacturer can currently handle around 30–60% hydrogen, with the majority of high-hydrogen turbines being aeroderivatives, such as the LM 2500 and LM 5000™ series [53]. Baker Hughes's newest line of turbines, the NovaLT™ series, is currently under R&D to increase the fuel flexibility, allowing up to 100% hydrogen. In this regard, Baker Hughes, in collaboration with Enel labs, continues to work on novel burner technologies to increase the reliability of lean, pre-mixed combustion of high-hydrogen fuels in their turbines [33].

MAN Energy Solutions has a portfolio consisting mostly of microturbines (6–12 MW). MAN's turbines generally use standard diffusion flame combustors, which can practically handle up to 60% hydrogen, but require post-combustion NO_X treatment in order to reach emissions targets. Several turbines are equipped with DLE technology, which can achieve very low NO_X without flame dilution. However, the allowable hydrogen percentage drops to 20% for these turbines. In collaboration with the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt [DLR]) at Stuttgart, MAN continues to conduct theoretical and experimental studies with the goal of achieving 100% hydrogen capability with minimal NO_X emissions [33].

Finally, Kawasaki Heavy Industries is also working on implementing novel combustion technologies and techniques to improve the reliability of hydrogen combustion in its turbines. To this end, current R&D efforts are focusing on a new "Micro-Mix" combustor (MMX) to reduce the effects of instabilities created by hydrogen combustion, helping to reduce NO_X. This technology is being developed in collaboration with Aachen University in Germany [54, 55]. The technology was successfully demonstrated in 2020, making Kawasaki the first OEM to successfully verify a 100% hydrogen-fueled turbine with DLN combustion technology. The demonstration project was carried out in partnership with Japan's New Energy and Industrial Technology Development Organization (NEDO) and Obayashi Corporation [56]. Using 100% hydrogen, the test system was able to provide 2,800 kilowatts (kW) of heating steam and hot water and 1,100 kW of electricity to various neighboring facilities while using water injection to achieve NO_X emissions of around 50 ppm, which is below the 70-ppm threshold set by Japan's Air Pollution Control Act [57].

5 CONCLUSION

Hydrogen combustion research continues to bear fruit to this day, and, while achieving 100% clean hydrogen combustion in gas turbines remains challenging, many successful attempts have been demonstrated by industry. Interestingly enough, aeroderivative engines appear to be leading the pack, with many models supposedly already able to make use of 100% hydrogen fuel with reasonable NO_X emissions. As mentioned previously, many companies, like Siemens, claim that several of their turbines are already capable of 100% hydrogen with diffusion combustors. However, such turbines are not marketable because the unmitigated NO_X emissions are too high. The major challenge with designing a 100% hydrogen combustion turbine is balancing the increased hydrogen usage limits against keeping NO_X emissions in check without sacrificing turbine efficiency. Such challenges have been the subject of extensive R&D over the past several decades that continues to this day. Without proper NO_X abatement techniques (SCR, SNCR, SoLoNOx, etc.) and combustor development, it has been predicted that the use of hydrogen will increase NO_X emissions by up to eight times compared to natural gas, depending on turbine specifications. However, with modern co-combustion and post-combustion abatement techniques, the studies and research efforts presented in this paper have demonstrated that a fully commercialized, low-NO_X, high-hydrogen turbine can be developed within the next 20 years with enough R&D.

Both public and private research initiatives are currently underway with the goal of achieving a fully commercialized hydrogen gas turbine power plant, as the majority of operational issues with hydrogen fuels have mostly been solved. Most OEMs continue to make progress and advance gas turbine technology so that the existing fleet can accept high-hydrogen fuels, and it is likely that a majority of the industry will have the capabilities to produce commercial-grade, 100% hydrogen engines by around 2030 based on current research progress and publicly announced forecasts.

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