LCRI LOW-CARBON RESOURCES INITIATIVE

EPRI GTI ENERGY

EXECUTIVE SUMMARY

HYDROGEN COFIRING DEMONSTRATION AT NEW YORK POWER AUTHORITY'S BRENTWOOD SITE: GE LM6000 GAS TURBINE

Advancing Clean Energy in New York: Green Hydrogen Pilot Project

The New York Power Authority (NYPA), EPRI, and General Electric (GE) are driving innovation to enable a cleaner energy future by leading a pilot project focused on hydrogen-fueled power generation. As part of the Low-Carbon Resources Initiative (LCRI), the companies jointly conducted a hydrogen blending project at NYPA's Brentwood Power Station. This collaborative effort demonstrated the burning of a hydrogen-natural gas blend on an LM6000 gas turbine (GT) to identify the resulting impact on combustion emissions (CO_2, NOx, CO) and GT operation. The GT was operated on hydrogen blends ranging from 5 to 44% by volume. The successful test represents the first utility-scale hydrogen blending project in the state of New York, which is mandating a zero-emission electricity sector by 2040 and calling for an orderly and just transition to clean energy and economy-wide carbon neutrality through the Climate Leadership and Community Protection Act.

About the Brentwood Power Station

The 45-MW Brentwood plant, located in Suffolk County on Long Island, New York, consists of a GE LM6000 GT equipped with single annular combustion (SAC) technology. SAC is not a dry-low emissions combustor technology and requires water injection for NOx control. The plant is also equipped with post-combustion catalyst systems for NOx and CO control. The plant's location and layout, combined with its relatively low capacity factor as a peaking unit, facilitated the temporary modifications required for this demonstration project (Figure 1). Working with EPRI, GE, and other industry collaborators, NYPA fired blends of 5–44% green hydrogen (by volume) with natural gas (NG) to identify and document the resulting impacts on LM6000 GT outlet emissions (CO_2, NOx, CO) and unit operation. Hydrogen cofiring was not performed during unit startup and shutdown operations.



Figure 1. Aerial view of Brentwood Facility.

Key Findings

- **Reducing CO_2 emissions**. CO_2 emission reductions followed the expected trends, decreasing as the hydrogen fuel percentage increased (Figure 2).
  - Reductions in the calculated CO_2 mass emission rates (ton/hr) with increasing hydrogen fuel percentages followed the expected trends. At 47 MWe, CO_2 mass emission rates were reduced by approximately 14% at 35% by volume hydrogen cofiring.
- **Ensuring regulatory compliance**. At steady-state conditions, the current selective catalytic reduction (SCR) and CO catalyst systems were able to control the stack NOx, CO, and ammonia slip levels below the regulatory permit limits (based on the current NG fuel permit) with hydrogen cofiring.

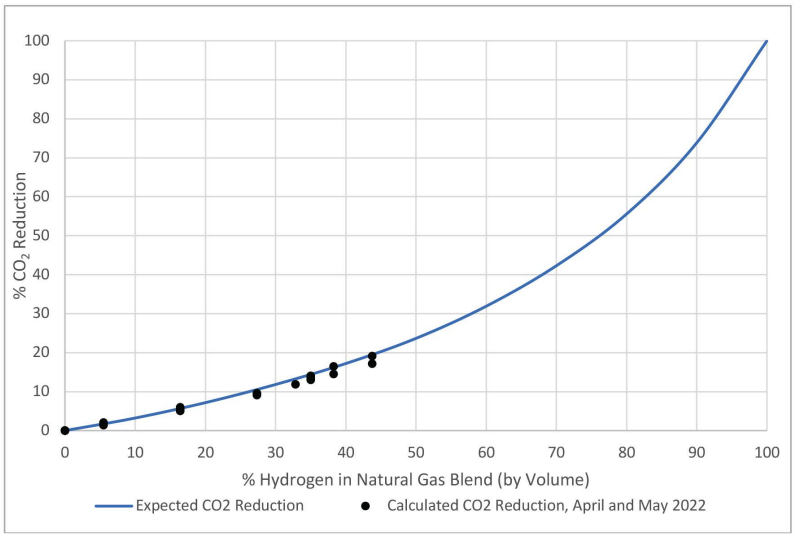


Figure 2. Expected and calculated CO_2 emission reductions for natural gas/hydrogen blends.

- **Understanding impacts on NOx and CO emissions at the GT outlet (upstream of the catalyst systems)**. At steady water injection rates based on burning NG, GT outlet NOx levels increased, and CO levels decreased as the hydrogen fuel percentage increased. By increasing water injection rates less than 20% by volume, GT outlet NOx levels were maintained at a constant level as hydrogen fuel increased to greater than 35% by volume.
  - **Observation: NOx increases at higher hydrogen levels.** During testing, GT NOx levels increased by up to 24% as the hydrogen fuel fraction increased. At the same GT load, maintaining a constant GT outlet NOx level while increasing the hydrogen fuel percentage required almost a linear increase in the water injection flow rate. It is important to note that this NOx increase observation is specific to LM6000 SAC technology and may not apply to dry-low emissions combustors.
    - **What it means**: Hydrogen cofiring could require LM6000 SAC operators to increase water injection (almost linearly with hydrogen fuel percentage) to maintain steady GT outlet NOx levels. If this is not an option and GT outlet NOx levels increase, owners may need to modify the existing SCR system design and/or adjust catalyst replacement intervals to maintain stack permit compliance, potentially increasing capital and operations and maintenance (O&M) costs.
  - **Observation: CO decreases with higher hydrogen fuel fraction**. CO levels decreased as much as 88% as the hydrogen fuel fraction increased during testing. Even with increasing water injection rates for NOx control, CO levels decreased with increasing hydrogen percentages. This is believed to happen due to enhanced CO oxidation in the presence of OH radicals formed during hydrogen combustion.
    - **What it means**: Depending on stack permit requirements, hydrogen cofiring could allow LM6000 units to operate across a wider load range without CO oxidation catalysts or with reduced volumes of catalyst, potentially lowering capital and O&M costs. LM6000 turndown capability could potentially improve due to the large reduction of CO caused by the introduction of hydrogen.

  - **Observation: NO_2/NOx fraction decreases with higher hydrogen concentrations**. As the hydrogen fuel percentage increased with steady water conditions, the NO_2/NOx fraction decreased by up to 61%.
    - **What it means**: This may benefit LM6000 turndown capability, as higher NO_2/NOx levels (above 0.5) at lower load temperature conditions could have a detrimental impact on the efficiency and performance of some SCR catalyst formulations.

- **NOx and CO measurements were repeatable** when comparing overlapping conditions between separate hydrogen tests.
- **Monitoring flame stability**. Vibrometer and dynamic pressure sensor measurements showed that combustion dynamics pressure (amplitude) did not increase with increasing hydrogen fuel levels, indicating that the flame remained stable.
- **Maintaining reliable operation**. No significant changes to GT operation were observed as measured by temperature and dynamic pressure sensors (which monitored combustion dynamics) during operation on hydrogen blends. GT control was stable without experiencing any trips during variations in fuel composition, provided that the lower heating value (LHV) and specific gravity data were transmitted to control software at the appropriate time.
- **Preserving asset integrity**. The periodic borescope inspection of the combustor during testing showed no apparent damage to the GT due to operation on hydrogen blends.

Operational Lessons Learned

- **Employ a collaborative design approach early on to help identify and overcome integration challenges**. The large number of teams involved with different design aspects of this project created situations where the design process was progressing at different speeds for each team. This led to rework late in the design process to ensure all the safety and operational requirements were met.
- **Maintain a stable hydrogen supply, which is critical to transitions of the hydrogen ratio and load of the turbine**. Instability of the hydrogen supply could cause the hydrogen system to trip off. Ensuring a stable hydrogen supply proved to be a challenge because of constantly adjusting the manual hydrogen regulators located separately on each hydrogen trailer connection (see Figure 3). The team was able to make the system work with significant manual intervention that required constant monitoring and adjustment during the test. This would not be practical for normal plant operation.



Figure 3. Hydrogen supply trucks.



Figure 4. Hydrogen blending system and gas analyzer.

- **Ensure adequate NG supply pressure for the increased volume demand created by the introduction of hydrogen**. As the hydrogen ratio increased, it was necessary to raise the NG supply pressure. This proved to effectively increase the limit of hydrogen that could be blended with NG (see Figure 4).
- **Evaluate the fuel gas analyzer for intended use**. If high-precision, lab-grade results are desired, the equipment should be designed appropriately, or samples should be pulled and sent to a lab, as was done during this test. If the goal is a stable, production-based operation, the equipment should be designed with that in mind, and a single type of analyzer should be used.
- **Provide sufficient time for a review of design concepts and to secure needed permit exceptions**. An early review of design concepts needed to include considerations for National Fire Protection Association (NFPA) codes and standards, as hydrogen is not well defined in the NFPA and an evaluation of considerations for vent and discharge locations is necessary. Securing the needed permit exceptions to allow the plant to operate in an "experimental" mode was a critical, but time-consuming, step. The permit exception allowed the plant to consume hydrogen, which was not part of the original permit, and would potentially cause the unit to exceed emission limits for the duration of the test.
- **Develop a list of applicable and required codes during the conceptual design stage**. Key considerations at this stage include understanding all code requirements, identifying good engineering practices, and differentiating "wants" from "must haves." An identified subject matter expert can provide solutions, alternatives, and guidance in response to complications associated with code requirements.
- **Keep leak testing fluids free of ammoniacal and chloride containing species**. Contamination has the potential to create material failure concerns.
- **Determine water quality prior to the hydrotesting of components**. It is generally recommended to use the best quality of water available for stainless steel, with the preference being (in decreasing order) demineralized water, high purity steam condensate, or potable water (with less than 50 ppm chloride, as required by several industrial standards).
- **Perform early "shakedown runs."** This preliminary step helps ensure instrumentation and recording of all data are reading and operating correctly.
- **Conduct post-construction testing**. Key activities include cleaning pipes and checking for leaks. Develop a list of requirements ahead of time; these activities will happen regardless of the final design of the system. Last-minute comments and requirements added complexity to the process.

Recommendations for Future LM6000 Hydrogen Cofiring Studies

- **Obtain dry emission data (without NOx water injection) to better quantify the impact of hydrogen on NOx emissions**. These data would be very useful to develop a correlation from which estimates of NOx water flow rates could be made for hydrogen cofiring. Note that obtaining dry emission data would require a permit to exceed site emission regulations.
- **Compile data on NOx versus CO trade-offs with water sweeps at maximum power at different hydrogen fuel concentrations**. Analyzing these data would help establish upper limits on water injection from the emission point of view.
- **Perform GT starts with increasing hydrogen fuel content to establish safe limits for startup**. For this project, the GT was always started on NG. Figure 5 depicts tube trailers with stanchions.
- **Pursue an expanded data set with GT temperature rakes**. Examining more data could help inform the operation of GTs in future hydrogen-blending projects.



Figure 5. Hydrogen trucks attached to stanchions.

Next Steps

Lessons learned during the design and execution of the project are documented in this report, along with recommendations for future LM6000 hydrogen cofiring investigations. Researchers will take this information into account in building a foundational knowledge base and exploring future hydrogen blending pilot projects as part of the clean energy transition.

The full report (3002025167) can be accessed at epri.com.

December 2022 Addendum

Testing Overview

- All site modifications and procedures complied with state and local safety codes and with current industry best practices
- Data shown here are based on hydrogen blending testing conducted at NYPA's Brentwood LM6000 Sprint unit
- Testing was conducted through multiple phases and each phase conducted over multiple days
- Major testing parameters varied during testing included load, water injection flow rate (used for all conditions on the turbine for NO_x control), and hydrogen content
- Emissions measurements at the gas turbine (GT) outlet included NO_x (NO_2 and NO), CO, O_2, and H_2O
- CO_2 emissions reductions with H_2 blending were calculated via fuel analysis data and combustion equilibrium calculations
- Combustion dynamics levels were measured throughout the testing

Testing Summary and Major Results

- Calculated CO_2 mass emissions were reduced by more than 14% at 35% H_2 by volume
- Based on testing conducted at different water flow rates, NOx was held constant while increasing hydrogen blending
  - Water flow rate required to hold NOx constant varied fairly linearly depending on NO_x target
  - CO reduction at 35% by volume H_2 was ~69% when increasing water flow rate to hold NO_x constant
- NO_2/NO_x ratio decreased with increasing H_2 blending
- Combustion dynamics measured during all testing indicated no increase with H_2 blending
- Table 1 is a summary of averages for measured GT outlet mass emissions and ratios over multiple tests at full load (46-47 MWg)
  - Note: Dry, volumetric NO_x measurements (ppmvd) have been converted to mass (lb/hr) due the effects H_2 fuel blending has on typical reporting methods[1]

1. *Douglas, C. M., Shaw, S. L., Martz, T. D., Steele, R. C., Noble, D. R., Emerson, B. L., and Lieuwen, T. C. (July 28, 2022). "Pollutant Emissions Reporting and Performance Considerations for Hydrogen–Hydrocarbon Fuels in Gas Turbines." ASME. J. Eng. Gas Turbines Power. September 2022; 144(9): 091003.* https://doi.org/10.1115/1.4054949

Table 1. Average GT Outlet Emissions Measurements for Hydrogen Variation at Full Load (46-47 MWg)

H_2 % by Vol	CO_2 [ton/hr]	CO_2 [ton/hr] *Ratio to 0% H_2*	Water Flow *Ratio to 0% H_2*	NO_x [lb/hr]	CO [lb/hr]	NO_x [lb/hr] *Ratio to 0% H_2*	CO [lb/hr] *Ratio to 0% H_2*	NO_2/NO_x Ratio
0	26.4	1.0	1.00	35.4	39.2	1.00	1.00	0.24
5	26.0	0.98	1.04	33.8	38.0	0.96	0.97	0.24
15	25.1	0.95	1.07	34.3	24.8	0.97	0.63	0.21
25	23.9	0.90	1.12	33.2	17.9	0.94	0.46	0.20
30	23.3	0.88	1.09	34.9	14.0	0.99	0.36	0.19
35	22.7	0.86	1.14	34.9	12.2	0.99	0.31	0.18
			Average emissions with increasing water flow in attempt to hold NOx constant (ratio of 1.00)					

- Table 2 below is a specific data set of measured GT outlet and exhaust stack mass emissions at near full load (46 MWg). This data set shows the ability of the current SCR and CO catalyst systems to keep the exhaust stack NO_x, CO, and ammonia slip levels below the regulatory permit limits (based on the current NG fuel permit limit of of 5 lb/hr), using increased water injection rates at the higher range of hydrogen fuel percentages.

Table 2. GT Outlet and Exhaust Stack Emissions Measurements for Hydrogen Variation at Near Full Load (46 MWg)

H_2 % by Vol	Water Flow [GPM]	GT Outlet NOx [lb/hr]	GT Outlet CO [lb/hr]	Exhaust Stack NO_x [lb/hr]	Exhaust Stack CO [lb/hr]	Exhaust Stack NH_3 Slip [lb/hr]
22	46.0	31.2	23.2	3.8	0.48	4.8
27	46.2	31.5	18.9	3.6	0.29	5.0
33	46.4	31.6	16.0	3.6	0.19	4.8
35	46.8	31.6	13.6	3.7	0.10	4.9

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

GTI Energy is a leading research and training organization. Our trusted team works to scale impactful solutions that shape energy transitions by leveraging gases, liquids, infrastructure, and efficiency. We embrace systems thinking, open learning, and collaboration to develop, scale, and deploy the technologies needed for low-carbon, low-cost energy systems.

www.gti.energy

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATIONS NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI) AND GTI ENERGY. NEITHER EPRI, GTI ENERGY, ANY MEMBER OF EPRI OR GTI ENERGY, ANY COSPONSOR, THE ORGANIZATIONS BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI OR GTI ENERGY.

THE FOLLOWING ORGANIZATIONS PREPARED THIS REPORT UNDER CONTRACT TO THE LOW-CARBON RESOURCES INITIATIVE (LCRI), WHICH IS JOINTLY LED BY EPRI AND GTI ENERGY:

EPRI
NYPA
GE

Note
For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

The Low-Carbon Resources Initiative

This report was published under the Low-Carbon Resources Initiative (LCRI), a joint effort of the Electric Power Research Institute (EPRI) and GTI Energy addressing the need to accelerate development and deployment of low- and zero-carbon energy technologies. The LCRI is targeting advances in the production, distribution, and application of low-carbon energy carriers and the cross-cutting technologies that enable their integration at scale. These energy carriers, which include hydrogen, ammonia, synthetic fuels, and biofuels, are needed to enable affordable pathways to economy-wide decarbonization by mid-century. For more information, visit www.LowCarbonLCRI.com.

TECHNICAL CONTACTS

Rob Steele, *Technical Executive*
980.229.2961, rsteele@epri.com

Tom Martz, *Principal Project Manager*
949.395.9647, tmartz@epri.com

3002025166 December 2022

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

© 2022 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ENERGY are registered marks of the Electric Power Research Institute, Inc. in the U.S. and worldwide.