Accelerating the technology roadmap for decarbonizing gas turbines via hydrogen fuel

By Junior Isles and Harry Jaeger

Siemens gas turbine engineers targeting field demonstrations by 2023 with 100% "green" hydrogen produced with surplus renewable energy, commercial projects by 2024-25.

The electric power sector in much of the world has made significant strides in cutting carbon emissions, largely through increased use of renewables such as wind and solar, and a shift from coal to natural gas-fired power generation.

Gas turbine industry attention is now directed at accelerating technology development and demonstration of "hydrogen readiness", or the ability to burn hydrogen as a carbon-free replacement fuel for natural gas, while still maintaining low NOx emissions.

During a webinar presentation earlier this year, Siemens reviewed scope, timing and goals for its hydrogen technology development and demonstration projects. Near-term projects:

- **10 MW SGT-400**. A commercial dry low emissions unit is being modified to operate initially in 2021 on a hydrogen and natural gas fuel blend with an incremental build up to 100% hydrogen.
- **24 MW SGT-600**. Two DLE gas turbines tested in 2019 on mixtures of up to 60% hydrogen by volume while maintaining 25 ppm NOx emissions are expected to begin commercial operation in 2021.
- **33 MW SGT-700**. Developmental hydrogen burner design based on additive manufacturing technology was tested on 100% hydrogen in 2019 while maintaining fairly low NOx emissions.
- **48 MW SGT-800**. Full engine sector testing in 2020 with a hydrogen-fed array of 5 burners (out of 30 burners) operating on 75% by volume hydrogen and 40 ppm NOx emissions.

Siemens is also participating in an industrial-scale integrated "Power-to-X-to-Power" hydrogen-fueled gas turbine demonstration HYFLEXPOWER project funded by the European Commission.

Purpose of this program is to demonstrate the commercial production of green hydrogen from renewable electricity for storage and use to replace natural gas fuel requirements for combined heat and power generation.

Partners on the project team include Engie Solutions, Centrax, Arttic, German Aerospace Center and four European universities. The demonstration site will be an existing SGT-400 combined heat and power facility at a Smurfit Kappa paper mill in Saillat-sur-Vienne, France.

Project timetable calls for development and installation of a hydrogen production, storage and supply facility at the demo site (2021), hydrogen modification and installation of the SGT-400 gas turbine (2022), and demonstration of the integrated system with 100% hydrogen (2023).

What makes this modified CHP plant unique is that the hydrogen gas turbine can fire any blend of natural gas and hydrogen, says Vinayaka Nakul Prasad, corporate strategy manager at Siemens Energy, enabling plant dispatch for full CHP operation with or without access to hydrogen fuel.

He points out that operating on 100% hydrogen only, with zero carbon emissions, could save up to 65,000 tons of CO_2 emissions per year for an SGT-400 gas turbine in normal baseload service.

Another research project of note is in the U.S. where Siemens Energy, Duke Energy and Clemson University are teaming up to study the use of hydrogen for energy storage and as a low- or no-carbon fuel source to produce energy at Duke Energy's CHP plant at Clemson University in South Carolina.

The pilot project will ramp up in March 2021 and include studies on hydrogen production, storage and co-firing with natural gas. Siemens Energy will study the use of its Silyzer electrolyzer to produce hydrogen fuel to help power the existing SGT-400 natural gas turbine at the Clemson plant.

Hydrogen combustion challenges

Jenny Larfeldt, senior gas turbine combustor expert, reported on work with several medium-sized machines developed in Finspång, Sweden – SGT-600, SGT-700, SGT-750 and the SGT-800 – and the effects of burning hydrogen.

The first technology issue tackled was the change in combustion flame color with increasing blends of hydrogen, ranging from blue to no color as the hydrogen volume reaches 100%.

"During high pressure tests on the

Hydrogen gas turbines. Siemens is preparing its gas turbine portfolio for dual fuel operation on natural gas and up to 100 percent hydrogen fuel mixture.

	Gas Turbine Model	ISO Base Output Natural Gas	Current Hydrogen Capabilities (by vol H_2)	CO_2 Reduction vs. 100% Natural Gas
50 Hz	SGT5-9000HL	593 MW	30%	11%
	SGT5-8000H	450 MW	30%	11%
	SGT5-4000F	329 MW	30%	11%
	SGT5-2000E	187 MW	30%	11%
60 Hz	SGT6-9000HL	405 MW	30%	11%
	SGT6-8000H	310 MW	30%	11%
	SGT6-5000F	215 to 260 MW	30%	11%
	SGT6-2000E	117 MW	30%	11%
50/60 Hz	SGT-A65	60 to 71/158 to 62 MW	15% 100%	5 / 100%
	SGT-800	48 to 62 MW	50%	23%
	SGT-A45	41 to 44 MW	100%	1006%
	SGT-750	40/34 to 41 MW	40%	17%
	SGT-700	33/34 MW	55%	27%
	SGT-A35	27 to 37/28 to 38 MW	15% 100%	5 / 100%
	SGT-600	24/25 MW	60%	31%
	SGT-400	10 to 14/11 to 15 MW	10% 65%	3 / 36%
	SGT-300	8/8 to 9 MW	30%	11%
	SGT-100	5/6 MW	65%	11 / 36%
	SGT-A05	4 to 6 MW	2% 15%	1 / 5%

Heavy frame gas turbines
Industrial gas turbines
Aeroderivative gas turbines

Dry Low Emission (DLE) burner
Wet Low Emission (WLE) burner
Diffusion burner w/unabated NOx

SGT-800, where we had 90% hydrogen and 10% natural gas, you can see the flame is still bluish, But as we get to 100% hydrogen on our DLE burners, the flame becomes invisible to the eye. This is not a problem because you can still see the flame in the IR spectra but it has to be considered in your flame detection system."

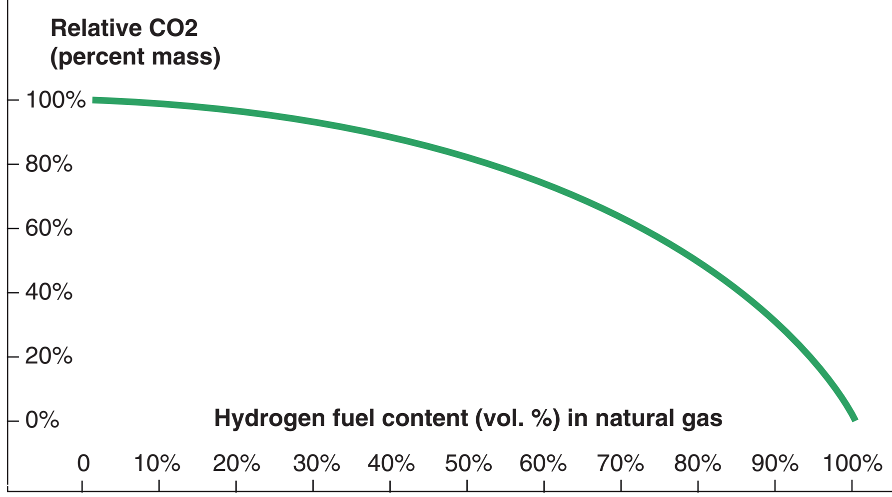
The fast burning nature of hydrogen is also a consideration. Hydrogen has a 10 times higher laminar flame speed than natural gas, a wider flammability range, a lower ignition energy, and a density much lower than natural gas.

Larfeldt noted, however, that density is not an issue because the Wobbe Index, a key measure of the interchangeability of fuel gases, is actually in the range considered normal for natural gas. "This means we can keep the same dimensions and sizing for our burners and auxiliary systems, pipes and valves," she noted.

Premix burner design

Siemens Energy uses a lean premix-type dry low emissions (DLE) burner design to control flame temperature and NOx production (flame temperature in the left image of ignition photos is the same as in the right image).

Mixed Fuel CO2 Emissions. Typically hydrogen and natural gas mixtures are defined on a volumetric basis; about 80% by volume H2 is needed to reach a 50% reduction in CO2 emissions.

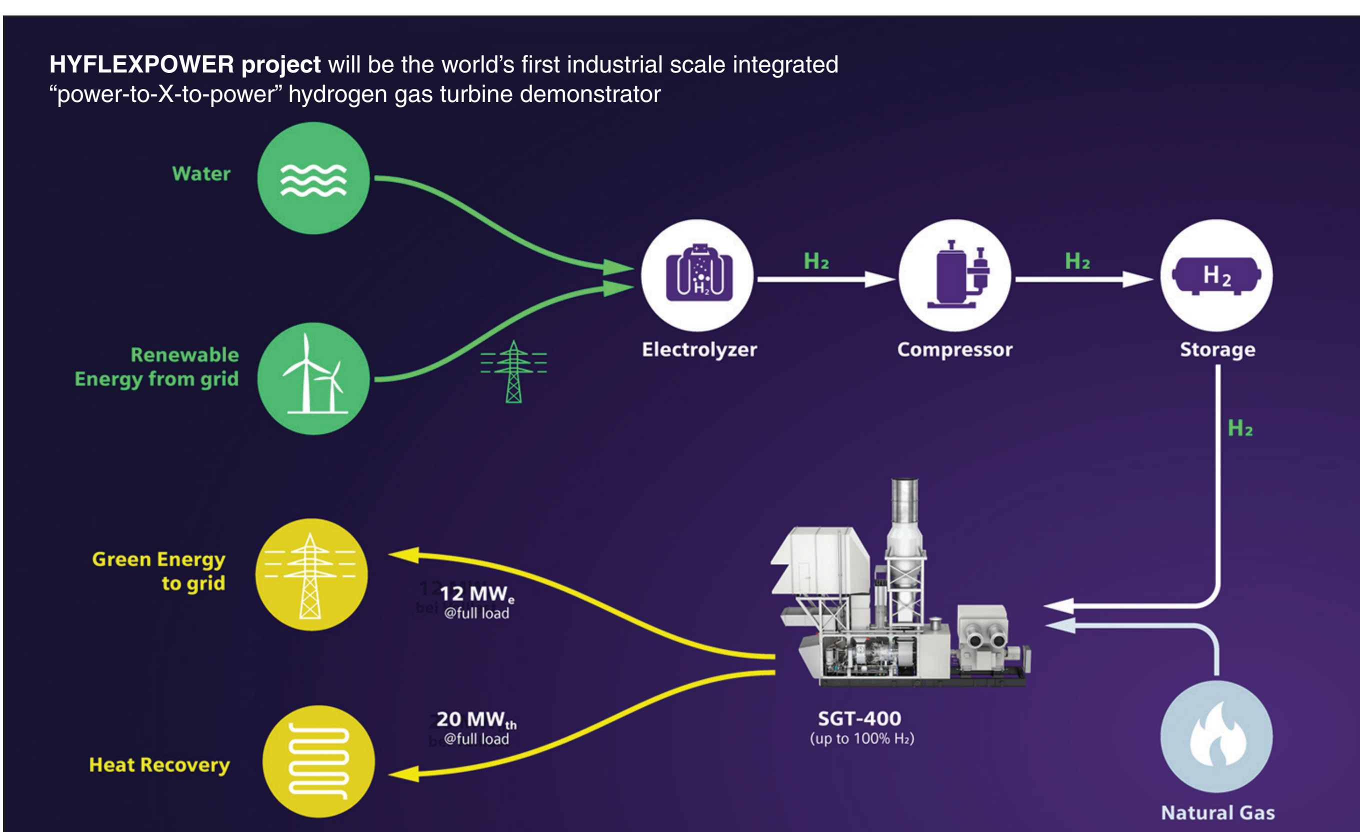


Source: Siemens

Compared to methane combustion in such burners, however, introduction of hydrogen causes the flame shape to flatten, become more intense, and move closer to the fuel injectors or "burner tips".

This is significant, Larfeldt pointed out, because "we need to accommodate this significant change in flame character while maintaining flame temperature and turbine inlet temperature in order to deliver the same amount of power."

As the flame becomes more compact and moves back toward the fuel injectors, she added, the heat load distribution changes and requires that the cooling design for the burner tip and adjacent area be modified. Also, air flow and fuel distribution must be optimized to avoid flashback.



Building on the past

Siemens experience with gas turbines burning high-hydrogen fuels dates back several decades, including numerous industrial units in the petro-chemical applications and large utility units operating on syngas produced by coal gasification. They list 55 units installed around the world, amassing 2.5 million operating hours on high-hydrogen fuel gases since the 1960s.

Extensive experience with high-hydrogen fuels on SGT-500 and SGT-600 industrial gas turbines burning refinery off-gases with up to 90 % by volume hydrogen content. For example, 10 SGT-500 units in the field have gathered over 800,000 combined operating hours on high-hydrogen fuels using non-DLE systems since 1979.

Today, the SGT-600, 700 and 800 use 3rd generation DLE technology. Over the last decade, development and testing of this burner has steadily improved its hydrogen capability.

In 2012, Siemens conducted field testing of a 30MW-class SGT-700 industrial unit with one of its 18 burners operating on a range of hydrogen-natural gas mixtures.

"In this full-engine test, we started out supplying a single burner with natural gas and up to 40% hydrogen by volume to observe and evaluate combustion performance. By 2014, encouraged by the results, test engineers had enriched the fuel to 60% hydrogen," said Larfeldt.

Other rig and engine testing over the last three years has cleared 55% on the SGT-700, and 50% on the SGT-800.

In 2017, Larfeldt continued, Siemens declared the technology to be "bid ready". This led to a commercial agreement for the installation of two SGT-600 DLE gas turbines for Braskem, a petrochemical company in Brazil.

Delivery tests in 2019 confirmed the turbines would run on fuel mixtures of up to 60% hydrogen by volume while maintaining 25 ppm NOx emissions at full load. Both units have also demonstrated reliable (off-design) operation on up to 80% hydrogen, are scheduled to begin commercial operation in 2021.

Concurrently, Siemens was also using additive manufacturing technology to develop advanced hydrogen burner designs around test results obtained at the company's high-pressure combustion test facility in Berlin, Germany.

"There we are free to specify design pressure, temperature and air flow to simulate actual operating conditions for all our different gas turbine frames," said Larfeldt, "and where we have successfully tested our pre-mix burners on up to 100% hydrogen while keeping relatively low NOx emissions."

SGT-800 hydrogen engine test

Meanwhile, partial sector testing was scheduled for the fall of 2020 on an SGT-800 gas turbine engine at the test facility in Finspång, conducted in a mechanical running testbed with a sector of 5 burners (out of 30) supplied with hydrogen.

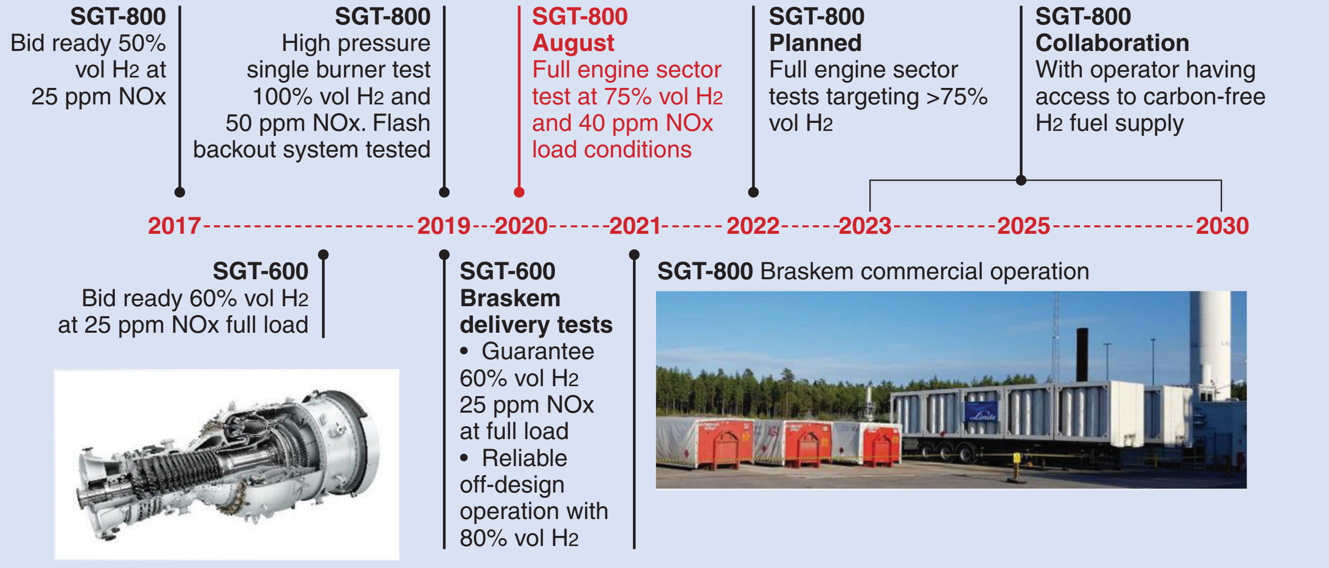
The target for this engine test was operation of the modified sector at up to 75% hydrogen by volume while maintaining 40 ppm NOx emissions. Operational testing under real engine conditions, on an actual engine, will capture the burner-to-burner interaction known to take place in an annular combustor.

Hydrogen delivered by Swedish suppliers will be stored onsite in five trailers at 250 bar pressure; two more trailers will also deliver gas from Germany. This amounts to 1.4 tons of hydrogen that can be used during testing.

With only a one-fifth sector of the full combustor annulus being fed hydrogen, this amount of stored hydrogen can support about 2 hours of testing. However, to extend testing to the full engine would require a much greater supply of hydrogen.

"If we run this unit on 100% hydrogen, which is our ultimate mission, that will allow only 20 minutes of operation," said Larfeldt. "The SGT-800 needs over 4.5 tons per hour so the 1.4 tons stored in the local trailers will not last very long

SGT-800 hydrogen R&D. Engineering design workhorse for development, test and demonstration of advances in hydrogen combustion technology for retrofit and new production models.



for full hydrogen operation."

Such massive consumption of hydrogen presents a supply problem in testing for long periods, and Siemens is therefore looking to collaborate with customers with access to large amounts of hydrogen.

Meeting EU target limits

Larfeldt noted that 75% by volume hydrogen corresponds to 50% hydrogen by energy in commenting on what this means in terms of performance and carbon emissions.

For example, in simple cycle mode burning natural gas fuel, the SGT-800 is rated at almost 40% efficiency with a CO_2 footprint of 500g/kWh.

"This would be reduced by half," she said, "if we successfully test on 75% by volume and bring us below the limit of 270g/kWh for carbon emissions, which has been suggested recently in the EU taxonomy as the limit for 'doing considerable harm."

For combined cycle installations on natural gas, where plant efficiency is 60% and CO_2 already at 330 g/kWh, to reach the 100g/kWh, considered as sustainable by the EU, 86% by volume hydrogen is required as the next step along the pathway to zero carbon emissions.

Future ready

Siemens Energy says that all the technology solutions in the works can be retrofitted to adapt its existing fleet of gas-turbines for operation on hydrogen fuel.

One serious issue with using high hydrogen-rich fuels in a pre-mixed burner is increased risk of flashback. Due to the combination its high flame speed, wide flammability limits, and the low ignition energy required, special care needs to be taken to avoid uncontrolled upstream flame propagation and auto-ignition.

Therefore, any hydrogen-adapted burner must be equipped not only with flashback detection capability, but also with a 'flashback-out' system.

With the flashback-out system, Larfeldt explained, the issue is mitigated by a brief 5-second water spray upon detection. "The system is only activated in event of a flashback – with the intention always being to keep the gas turbine running. We are well aware that the customer priority is to operate without interruption."

"This is why we developed the flashback-out system, which is similar to our pilot recovery system. This will also be installed and run on the two units in Brazil."

For an existing installation, the fire protection system and enclosure ventilation must be reconfigured for hydrogen. You also must check out the classification of your electrical equipment and adapt your hazardous area classification, Larfeldt advised.

Supporting programs

Continuing work on hydrogen solutions will be supported by the Zero Emissions Hydrogen Turbine Center in Finspång on a project funded by the Swedish Energy Agency and EU ERA-Net Smart Energy System.

Here, Siemens Energy is working with Chalmers University of Technology and University of Bologna, Linde AG, the Municipality of Finspång, and the County Administrative Board of Östergötland.

A primary mission of the 3-year project, which began December 2019, is to reduce the waste of power in load banks during gas turbine workshop tests. Part of this power will produce hydrogen via electrolysis, for subsequent tests mixed into the turbine fuel gas, thus reducing LNG consumption. Since gas turbine tests only run once a week, solar panels will be installed to ensure continuous production of hydrogen.

Siemens Energy is keen to collaborate with customers on hydrogen-related projects. One, already in place with Göteborg Energi, is to modify an existing gas turbine CHP plant for compliance with a new local requirement that by 2025 all district heating in Gothenburg must be produced by renewables or recovered energy sources.

The Rya CHP plant is powered by three gas-fired SGT-800s and a steam turbine rated at 264 MWe and 295 MWth

Combustion characteristics. Hydrogen has a 10 times higher laminar flame speed than natural gas, wider flammable region, much lower ignition energy.

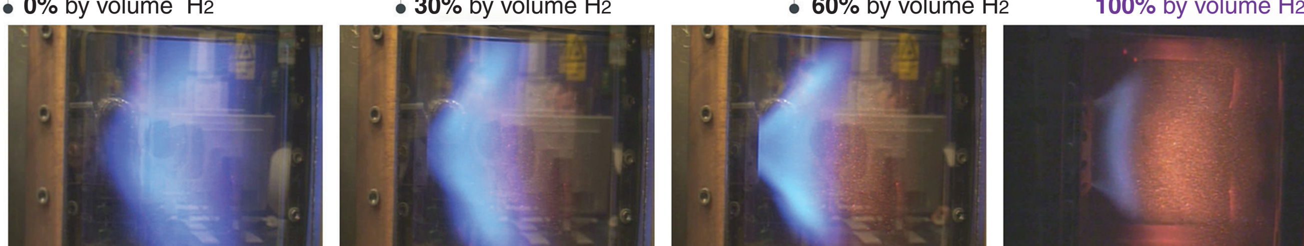
Hydrogen ignites and burns fast …
Combustion moves flame closer to the injector. Hydrogen flashback can be countered by optimizing combustion air and fuel distribution.

Hydrogen has a wide flammable region …
Much wider range of fuel-to-air ratio to burn than natural gas, Calls for compatible ventilation, gas detection and fuel systems.

Hydrogen has a low ignition level …
Only a fraction of the ignition energy is needed to get hydrogen 'going' as compared to natural gas combustion.

Hydrogen also has lower density …
Not an issue, fortunately the Wobbe Index for hydrogen fuel remains in the natural gas range of 37 to 49 MJ/nm3.

0% by volume H_2 | **30%** by volume H_2 | **60%** by volume H_2 | **100%** by volume H_2



full load output, The plant will serve as a host site to help project engineers develop and test a dual fuel burner in commercial service on green gaseous and liquid fuels. Start-up operation is scheduled for 2024.

Larfeldt noted that additive manufacturing technology has expedited engineering development of new burner designs by rapidly converting R&D concepts into prototype hardware for operational test evaluation and component.

Additive manufacturing can also be used to repair and modify existing burners, opening the potential for building new functionality into burners under repair or overhaul.

For Siemens Energy, it's also about switching from traditional supply chains to its own additive manufacturing centers, the one in Finspång and others in Berlin, the UK and Orlando."

Looking forward

Siemens Energy plans to eventually roll-out the new burner technology for its large heavy frame turbines such as the advanced HL machines.

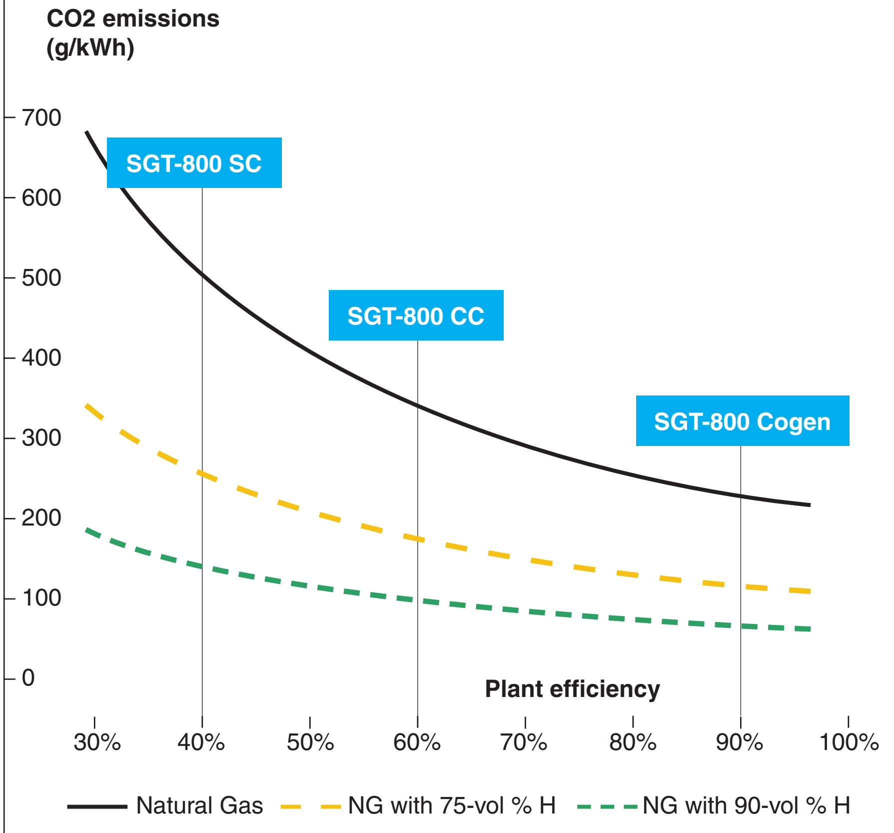
These already can burn gas fuel mixtures of 30% hydrogen by volume, but not likely to see operation on 100% hydrogen until 2030 depending on availability of hydrogen fuel.

Prasad noted that the primary long-term obstacle in the transition to carbon-free fuel is "supplying the level of hydrogen needed. The larger engines require a lot of hydrogen, so that's also a challenge, particularly if the source of hydrogen supply is to be green."

Larfeldt added: "With the smaller and medium-sized industrial gas turbines, we had an early start with the development and already have customers producing process gases that are hydrogen-rich. These eventually will have to be green too."

So, work will continue with the long term objective in mind. As Prasad summed it up: "Because hydrogen is very likely to be part of our energy future and can be used in current assets with relatively modest upgrades and modifications, we continuously work to improve upgrade packages to ensure that owners of Siemens gas turbines can economically future-proof their assets." ■

Hydrogen CO_2 Footprint. Switching an SGT-800 combined cycle plant running on natural gas to a fuel mix of 75% by volume hydrogen will cut gas turbine CO_2 emissions by 50 percent.



Scope of future-ready packaging. Integrated design concept for SGT-800, SGT-700 and SGT-600 gas turbines equipped with 3rd generation DLE combustion to prepare them for dual fuel operation on natural gas and hydrogen blended fuel.