Turning to sequential combustion technology to push hydrogen fuel content to the extreme

By Andrea Ciani, Michael Düsing and Gerhard Früchtel, Ansaldo Energia
Edited by Harry Jaeger, GTW

Ansaldo Energia, teaming with European partners, is leveraging the inherent fuel flexibility advantages of sequential combustion technology aiming to reach commercial 100% hydrogen combustion soon.

As the world moves towards net-zero power generation with increasing reliance on renewable energy sources, decarbonization of gas turbine assets via low-carbon or carbon-free fuels is seen as playing a vital role in the transition of the energy landscape, allowing them to continue offering unmatched operating flexibility and energy storage services.

This puts a focus on hydrogen as an alternative to natural gas, making it an essential "energy pillar" in the transition by enabling low carbon, or even CO_2-free dispatchable power generation.

The recently launched FLEX4H2 project, being carried out by a consortium of European companies and research partners, is led by Ansaldo Energia. It aims to develop a fuel-flexible gas turbine combustion system for hydrogen fuel. The design, based on constant pressure sequential combustion (CPSC) technology, will be able to operate safely, reliably and efficiently with any hydrogen/natural gas blend up to 100% hydrogen.

This ambitious design goal addresses the typically cited technical challenges when considering the switch from natural gas to hydrogen fuel, including:

- Avoiding flashback
- Controlling NOx emissions
- Maintaining flame stability
- Broadening fuel flexibility

The intent is for the improved CPSC combustor design approach to be retrofitable to existing gas turbines, providing significant opportunities for upgrading existing generation assets.

The FLEX4H2 project will present credible pathways for widespread exploitation of the project's results and provide the basis for a solid contribution to the EU Green Deal towards decarbonization of the electric power sector (see editorial box).

Challenges of hydrogen combustion

The transition towards a hydrogen-based energy system dictates the need for fuel flexible gas turbines equipped with combustors capable of coping with a wide range of natural gas/hydrogen-mixtures and with rapid changes in the fuel composition.

Due to its high reactivity, hydrogen strongly alters the combustion properties of the fuel in comparison with natural gas (primarily methane, CH_4). Adding hydrogen to natural gas increases its flame speed, reduces its ignition delay time, and enlarges the fuel's flammability limits.

This is illustrated in Table 1 which summarizes physical and combustion properties of hydrogen and compares them to those of natural gas (represented by CH_4).

These differences in properties substantially affect flame behavior, leading to major challenges to be addressed in designing robust and reliable combustion systems for low-emissions high-efficiency gas turbines burning a highly reactive fuel such as hydrogen.

Table 1. Hydrogen combustion properties. Differences between the most relevant combustion properties of natural gas (CH_4) and hydrogen (H_2) substantially affect flame behavior.

Combustion Properties	Natural Gas	Hydrogen
Lower heating value	50.3 MJ/kg 33.9 MJ/Nm3	119.9 MJ/kg 10.2 MJ/Nm3
Laminar flame speed	0.43 m/s	3.50 m/s
Stoichiometric combustion temp.	2227°K	2370°K
Density	0.72 kg/Nm3	0.09 kg/Nm3
Specific heat	2.18 kJ/kg°K	14.24 kJ/kg°K
Flammability limits	5 to 15%	4 to 75%

Let us briefly look into these design challenges one at a time.

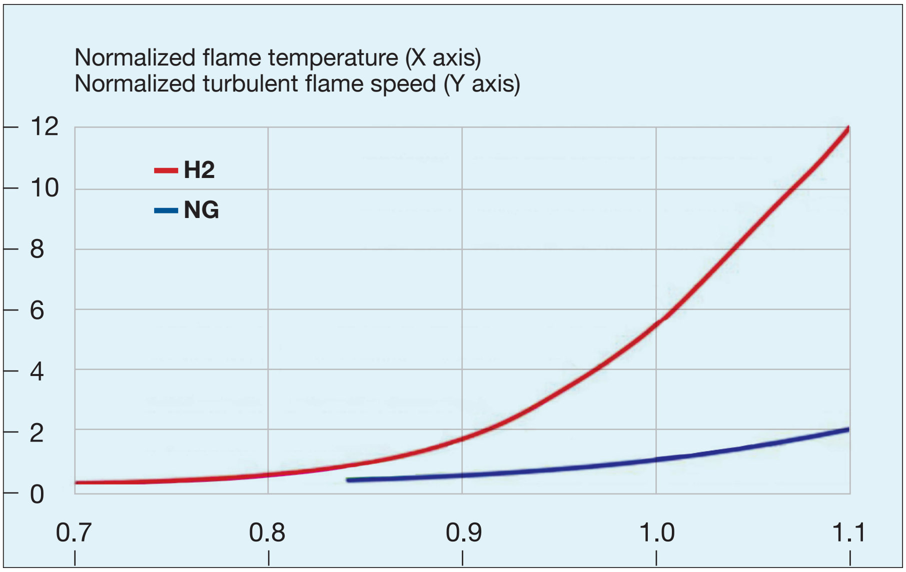

Figure 1. Effect of hydrogen and flame temperature on flame speed. Curves compare normalized turbulent flame speed vs. normalized flame temperature for hydrogen and natural gas fuels. Steep rise in hydrogen flame speed at high load (high flame temperature) raises challenge of flash back.

Avoiding flashback

Within the combustion system, due to the significantly increased reactivity and thus flame velocity (note the eightfold increase in the flame speed reported in Table 1), avoiding flashback is the most severe challenge for H_2 combustion.

Flashback in a gas turbine combustor can damage hardware within seconds and thus needs to be strictly avoided.

To prevent flashback, the design must be such that the flame cannot travel upstream into the burner. This requires that, at any time and location, the flow velocity must be high enough to push the flame sufficiently downstream of the burner, where fuel and air are mixed.

Given the higher flame speed of H_2 compared to natural gas, the air velocity within the burners should also be increased, which in typical dry low NOx premix systems would imply an unacceptable impact on burner pressure loss, and on gas turbine power and efficiency.

As illustrated in Figure 1, the H_2 flame speed strongly increases with the equivalence ratio (represented by adiabatic flame temperature) and it is also characterized by a stronger dependency on pressure when compared with natural gas. Therefore, flashback is likely to appear first at high loads associated with high flame temperatures.

Controlling NOx emissions

Similar to natural gas combustion, but even more so due to higher flame temperatures, NOx emissions pose a serious challenge in H_2 combustion.

Because of the oxygen (O_2) and nitrogen (N_2) in air, the combustion of H_2 at high temperatures causes reactions that produce oxides of nitrogen (NO and NO_2), the primary constituents of harmful NOx emissions.

Since the formation of NOx emissions are strongly driven by local peak temperatures, thorough mixing of fuel and air to avoid such temperature maldistribution is crucial in the effort of maintaining low emissions levels.

The high reactivity and high flame temperature of H_2 dramatically amplifies the detrimental effects of unmixed flow on NOx emissions. Therefore, rapid mixing of both streams (at high velocity) is of even greater importance compared to the combustion of natural gas.

Maintaining flame stability

The dynamic behavior of hydrogen-based flames is also very different from that of flames burning natural gas. Increased flame propagation speed and local heat release rates strongly influence the flame structure, and thus the thermo-acoustic response of premix combustion systems.

A sequential combustion system, thanks to the complementary behavior of its two combustion stages, relies on

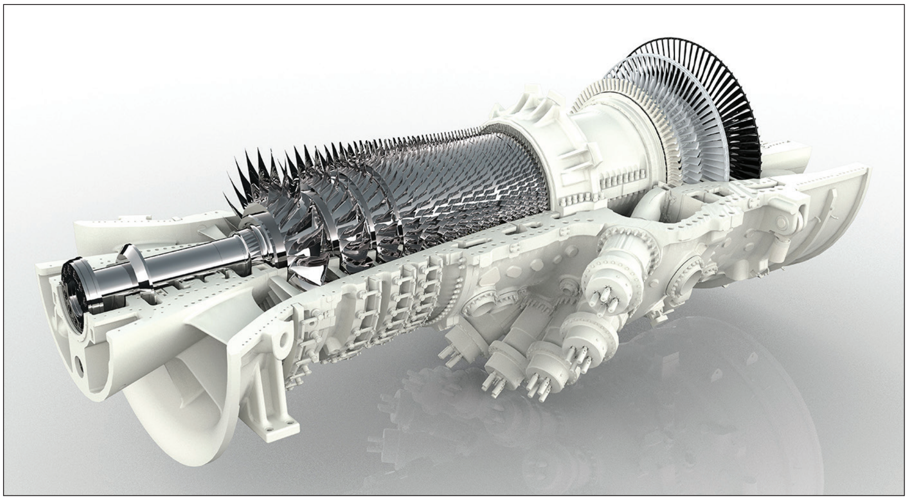

Figure 2. The GT36 gas turbine. Ansaldo's 50Hz H-class gas turbine has a simple cycle ISO rating of 563MW and 7935 Btu/kWh heat rate (43% efficiency) on natural gas fuel. Combined cycle (1-on-1) rating is 800MW at 5450 Btu/kWh heat rate (62.6% efficiency).

different flame stabilization mechanisms and offers an effective solution to this as well as other H_2 combustion related challenges.

CPSC technology

Ansaldo Energia has successfully implemented constant pressure sequential combustion (CPSC) technology in its state-of-the-art high-efficiency heavy frame gas turbines such as the GT36 (Figure 2), applicable to both 50 and 60 Hz markets.

This represents the most promising technology to achieve stable, clean and efficient hydrogen-firing of H-class gas turbines and supports technology development efforts being carried out under the FLEX4H2 program.

The CPSC combustor consists of a primary chamber (first stage) and a sequential chamber (second stage), arranged in series within a longitudinally staged architecture working at nearly the same pressure (see GT36 combustor, Figure 3).

A dilution-air section between the two stages allows a portion of the combustion air to bypass the first stage and is used to optimize the inlet temperature of the second stage.

The possibility to adjust the second-stage inlet temperature constitutes an intrinsic control knob which makes the combustion system more flexible than conventional gas turbine combustors (see editorial box #2). It also makes the combustion system resilient to wide variations in fuel reactivity and engine load.

Built upon field experience

The development of Ansaldo Energia's GT36 CPSC combustor was built upon the proven F-class GT24/26 sequential combustor design and advanced the technology to the next level. This evolution benefited both from 25-years of GT24/26 field experience and from the freedom which a new gas turbine platform offers.

Various measures taken to optimize the integration of the GT36 CPSC combustor into the gas turbine system resulted in further improvements in operational flexibility. This now paves the pathway to 100% H_2 combustion and allows the engine to achieve highest utilization and dispatch in dynamic power markets.

Figure 3 shows a comparison of the GT26 and GT36 sequential combustion systems. Both feature two combustors in series. The first combustor houses an aerodynamically stabilized premixed burner, while the second combustor consists of a sequential burner stabilized via self-ignition.

Although the GT26 combustors are annular, maintainability has been significantly improved using can-type combustors within the GT36, allowing combustors and other key hot-gas parts to be removed without lifting the casing of the engine.

Implementation of can-type combustors greatly benefited from improved rig-to-full-scale-engine transferability of new features tested in single can test rigs. This has been extensively used during the initial GT36 design and now supports the development towards 100% H_2 fuel. In addition, the overall engine architecture was further

The European Green Deal

As part of the European Green Deal, the EU has set itself the binding target of achieving climate neutrality by 2050 with the European Climate Act.

This presupposes that current greenhouse gas emissions will decline significantly over the next few decades.

As an intermediate step on the road to climate neutrality, the EU has formulated even more ambitious climate targets for 2030 and committed to reducing its emissions by at least 55% by 2030.

In this respect, considerable efforts have been made in recent years regarding the large-scale deployment of renewable energy sources to the energy system alongside with improving energy efficiencies, which are the main drivers for reducing greenhouse gas emissions.

The share of renewable energy sources (RES) in EU28 energy production has steadily grown from 8.5% in 2004 to 22.1% in 2020 and is targeted to reach at least 42.5% in 2030.

Other world regions have similar ambitious targets. USA is targeting, with the Inflation Reduction Act from 2022, to change its Energy Industry funding green technologies. Also, China aims at carbon neutrality by 2060.

One of the main difficulties accompanying the massive deployment of renewable energy sources is its intermittent nature and limited predictability, thus energy supply rarely matching the actual demand on the grid.

As the share of renewable energy into the electricity grid increases, the ability to match this unscheduled intermittent supply with demand becomes increasingly challenging, ultimately threatening the stability of the electricity grids.

simplified, removing the high-pressure turbine between the two combustors.

Intrinsic fuel flexibility of CPSC

The possibility of utilizing two flame stabilizing methods adds to the intrinsic fuel flexibility of the CPSC system.

The first stage (premix) combustor utilizes swirl-stabilized propagating flames, providing excellent flame stability and combustion efficiency over an extensive operational range. The second stage (sequential) combustor is primarily self-ignition controlled.

These two contrasting methods of controlling the flames provide a substantial advantage in minimizing NOx emissions at base load while maximizing the engine's turndown capability. In addition, they create a unique advantage with fuel flexibility, specifically for highly reactive fuels such as H_2.

While conventional dry low emission (DLE) combustion systems, based on lean premix technology, are limited to relatively low hydrogen concentrations due to increased flame propagation speed with hydrogen, sequential combustion systems, thanks to second-stage self-ignition combustion, can circumvent such limitation. This is due to the lower sensitivity to equivalence ratio and the intrinsic complementary interplay between the two sequential combustion stages.

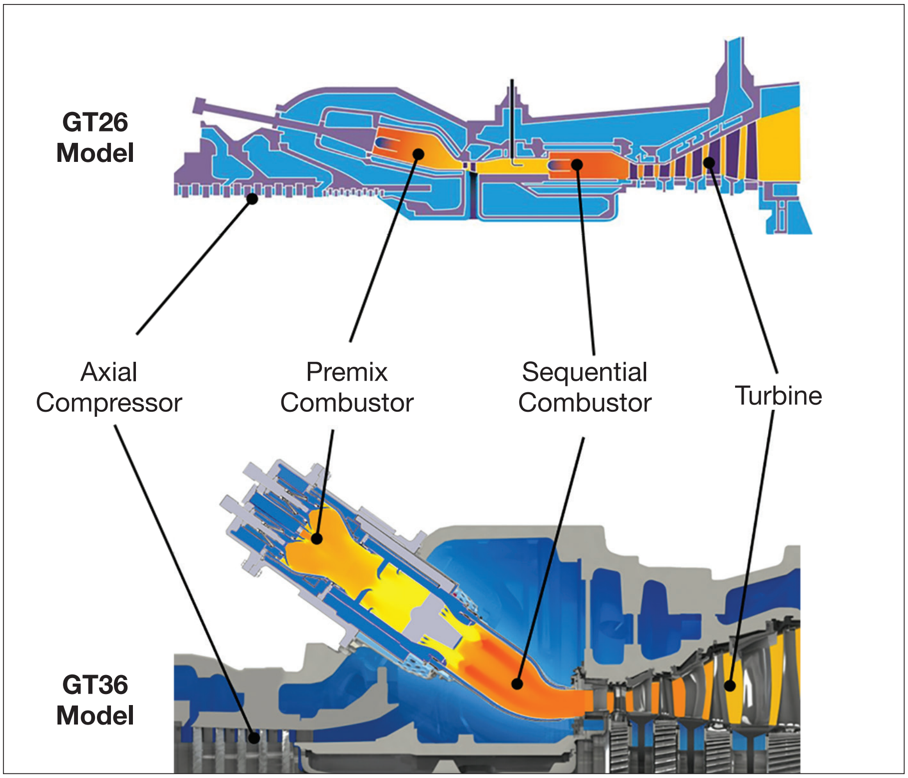

Figure 3. Comparative combustor architecture. The F-class GT26 includes a high-pressure turbine between two combustors which operate at different pressures. This is replaced by a dilution air mixer in the H-class GT36 constant pressure sequential combustion system.

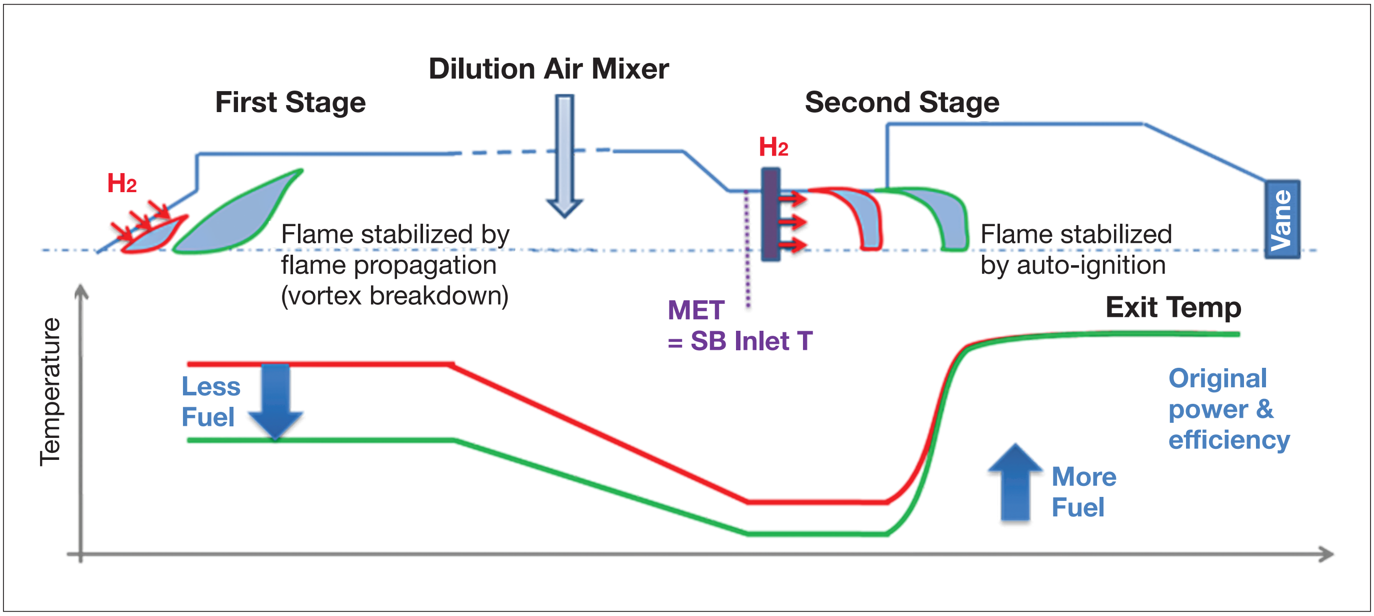

Figure 4. Constant Pressure Sequential Combustor (CPSC) schematic. The GT36 features inherent and unique fuel flexibility enabling switching from natural gas (red temperature profile) to hydrogen (green temperature profile) by reducing fuel flow to first stage and increasing fuel to second stage, which maintains original burner exit temperature, power output and efficiency.

Specifically, the CPSC flexibility stems from the ability to manipulate the flame temperature in the first stage and the location of the self-ignited flame in the second stage (Figure 4) by adjusting operational parameters in real time.

If, for example, instead of natural gas (red temperature profile), a more reactive fuel, i.e. H_2 (green temperature profile), is burned, the first stage temperature is reduced by reducing fuel flow, while fuel flow to the second stage is increased to keep the second stage flame at its design position.

This simple fuel shift from the first to the second stage is also beneficial in maintaining the first stage flame at its optimum location thanks to the correspondingly reduced first stage equivalence ratio.

Thus, the CPSC concept yields the best fuel flexibility and therefore has the greatest potential to achieve the FLEX4H2 program goals of stable and clean combustor operation with pure H_2 or natural gas, and any intermediate blend, maintaining the high firing temperatures typical of modern H-Class engines (2700 °F/1500 °C+).

CPSC testing on hydrogen fuel

Using GT36 production engine single-can hardware developed for pure natural gas, benchmark high-pressure combustion tests have been carried out over a full range of hydrogen/natural gas fuel blends in a test rig reproducing full engine operating conditions, including temperatures, pressures and flows (Figure 5).

Thanks to the above-mentioned flexibility, it was possible to run with up to 70%(v) H_2 maintaining full load H-class temperatures without hardware modifications, mainly by adapting the CPSC operating concept.

Operating this standard natural gas combustor even up to 90%(v) H_2 was also possible by slightly reducing exit temperatures levels for better flame stability. The combustion system proved able to adapt to rapid fuel composition changes.

Constant Pressure Sequential Combustion (CPSC) Built-in Fuel Flexibility

The sequential combustion system comprises two combustion stages in series. A first (upstream) stage is stabilized by flame propagation in a swirling flow, while the second (downstream) stage is stabilized by self-ignition.

Turbulent flame speed, which is primarily driven by equivalence ratio and fuel composition, defines the flame location of the first stage, while the second stage inlet temperature with its fuel composition constitutes the main factor defining the flame location of the second stage.

With any major change in fuel reactivity, e.g. replacing natural gas with a hydrogen-based fuel, the flame will tend to flash back due to faster flame propagation speed and shorter self-ignition time.

In CPSC systems, however, the effect of the higher fuel reactivity can be compensated for by adjusting the fuel split between the first and the second stage.

Sequence of events when fuel reactivity increases (e.g. with higher hydrogen content):

a) less fuel is injected in the first stage,
b) resulting lower equivalence (fuel/air) ratio in the first stage brings the turbulent flame speed to optimum values for best first stage performance,
c) lower first stage flame temperature produces a lower inlet temperature to the second stage,
d) lower second stage inlet temperature brings the self-ignition time to optimum values for the second stage,
e) the second stage flame is at its design location ensuring best combustor performance, and
f) more fuel is injected in the second stage to recover the power loss in the first stage.

Note that the higher equivalence ratio in the second stage has minimal impact on self-ignition time, thus does not compromise the beneficial effect of the lower inlet temperature on flame location.

Figure 6 shows flame images observed during testing with varying H_2 content. One can clearly notice how the temperature of the first stage flame was lowered by reducing the fuel flow as H_2 concentration is increased, while the fuel to the second stage is increased to maintain its flame structure and, most important, hold a constant combustor exit temperature.

Exploiting full potential of CPSC

The CPSC system already deployed in the Ansaldo Energia GT36 H-class gas turbine has demonstrated the potential to operate with every natural gas/hydrogen blend. Therefore, it is not only an enabling technology for future CO_2-free dispatchable power generation, but also for providing the required fuel flexibility to utilize increasing concentrations of hydrogen blend to enable the phasing out of natural gas during the energy transition phase.

Crucially, this objective will be pursued at the most challenging hydrogen combustion conditions, i.e., at H-class operating temperatures, required for highest cycle efficiency, while still meeting emission targets.

The FLEX4H2 program recognizes that optimization of the system and its technology maturity for blends with H_2 content close to 100% still require further development, in particular to ensure flame stability. This development will need to be based on all disciplines involved in the design of modern combustion systems.

The design of the improved hydrogen combustor, based on Ansaldo Energia's CPSC technology, will be demonstrated in a stepwise approach, at full H-class gas turbine operating conditions. The plan is to achieve program objectives by 2026.

FLEX4H2 program

The recently launched FLEX4H2 joint project, being coordinated by Ansaldo Energia, aims at developing a combustion system able to operate on every hydrogen/natural gas blend, whilst maintaining high engine performance, efficiency, operating flexibility, and low NOx emissions without diluents.

The engineering development effort itself will be carried out using the combined skills and know-how of the FLEX4H2 project consortium members comprised of eight partner organizations, covering six countries.

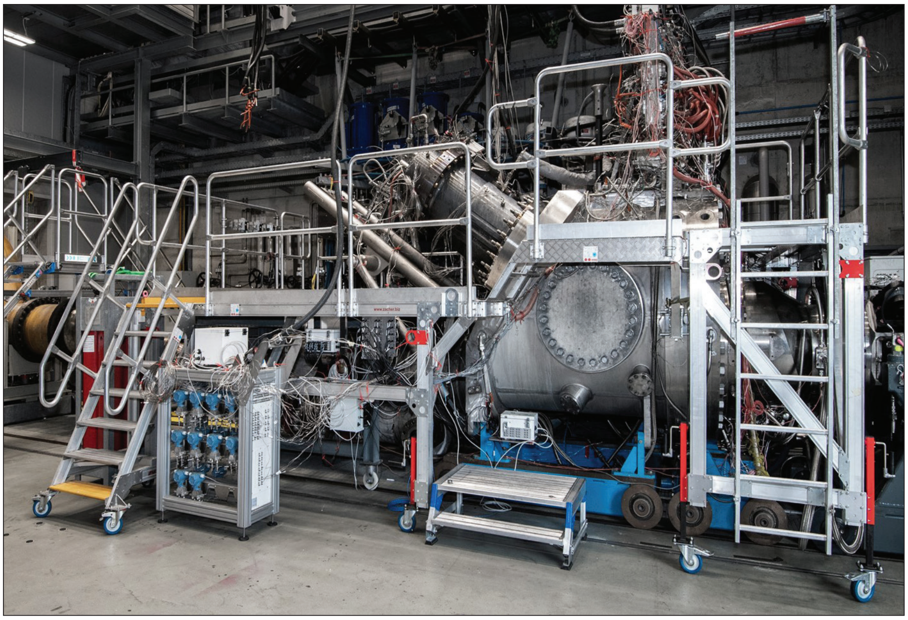

Figure 5. GT36 single-can high pressure combustion test rig. Development, verification and implementation of can-type combustor designs greatly benefit from improved rig-to-engine transferability of new design features tested in single-can test facility at DLR Cologne.

- ***Ansaldo Energia*** – Gas turbine Original Equipment Manufacturer (OEM) – project coordinator
- ***ARTTIC Innovation*** – Consulting company for publicly funded research and innovation
- ***CERFACS*** – European Center for Advanced Research and Training in Scientific Computing
- ***DLR*** – German Aerospace Center, Institute of Combustion Technology
- ***Edison*** – Italian electric utility and power plant operator
- ***ETN Global*** – Non-profit membership association bringing together the entire value chain of the gas turbine technology
- ***SINTEF*** – Independent European research organization
- ***ZHAW*** – Zurich University of Applied Sciences, Institute of Energy Systems and Fluid Engineering

The project will utilize a broad portfolio of state-of-the-art computational tools, analytical modelling, and diag-

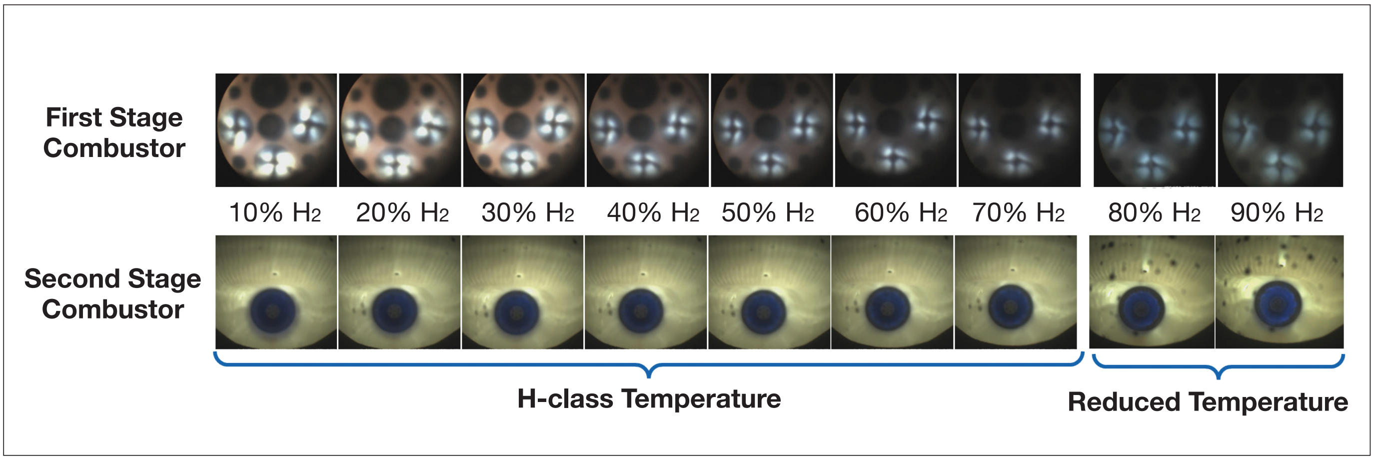

Figure 6. Flame images with varying fuel-blend composition. With increasing hydrogen content, fuel flow to the first stage combustor (top row) is reduced to lower flame temperature, while the fuel flow is increased in the second stage combustor (bottom row) to maintain constant H-class exit temperature. At greater than 70% (v) H_2, second stage exit temperature was slightly reduced to improve flame stability.

nostic techniques to investigate static and dynamic flame stabilization.

Testing is to be performed at world-class laboratories in test campaigns at reduced scale and in full size at atmospheric and pressurized conditions.

The key to success of this project lies in the well-balanced multidisciplinary composition of the consortium, bringing together one of the world's leading players in the sector of power generation plants with renowned leading research partners, a gas turbine industry stakeholder representative association, and a major power plant operator.

All consortium partners have a long and successful history of collaborating in European, national and other research projects.

Project work structure

The FLEX4H2 project effort has been divided into six distinct, yet closely interrelated, work packages (WP1-6) structured as shown in Figure 7.

Within ***WP1*** Ansaldo Energia, one of the world's leading gas turbine OEM and coordinator of the FLEX4H2 project, is leading the development of the combustion system towards a Technology Readiness Level (TRL) 6. This will be done in close coordination with ***WP2***.

This work package was assigned to the highly renowned combustion modelling research institutes CERFACS and SINTEF, the former focusing on high-fidelity numerical simulations in the first combustor stage, the latter focusing on the sequential combustion stage (Figure 8).

Based on the numerical simulation results, ***WP3*** entails further in-depth analytical modelling, low TRL experiments, and testing and mitigation strategies to be performed at the Zurich University of Applied Sciences, with a focus on thermoacoustic pulsation dynamics to ensure stable operation of the combustion system.

WP4 involves experimental studies to be performed at the high-pressure

Germany's RWE chooses Ansaldo Energia's GT36 for new hydrogen-ready 800MW combined cycle plant

RWE, Germany's leading power producer, announced that it signed a contract with the consortium formed by Ansaldo Energia and Spanish EPC contractor Técnicas Reunidas, for the engineering, supply and construction of a hydrogen-ready combined cycle plant.

In announcing the July, 2023 contract signing, RWE said that the project is part of the company's, and Germany's, overall decarbonization and energy transition plan.

The new combined cycle plant will be sited at RWE's existing Weisweiler lignite-fired power plant near Cologne. It will be ISO rated at 800MW at over 62% efficiency.

Under the contract, Ansaldo Energia is to supply the entire power island, the heart of the combined cycle plant, which includes the 563MW GT36 gas turbine generator, a nominal 250MW steam turbine generator, HRSG, condenser, and related auxiliary systems.

Técnicas Reunidas work will include the engineering of the permitting phase (which is to start immediately), the project engineering, supply of plant auxiliary equipment, and the construction, commissioning and start-up of the plant.

Ansaldo Energia says that the GT36 gas turbine can already operate with a blend of 50%(vol) hydrogen thanks to its unique sequential combustion system, with the potential to upgrade to 100% hydrogen.

The existing Weisweiler power plant site contains four lignite-fired steam power plants, which are scheduled to be closed under the German Coal exit law. The planned combined cycle plant will thus help to provide dispatchable generation while reducing climate-changing emissions, and allow further penetration of intermittent renewable energy in the German power market, says RWE.

Final investment decision (FID) for new project awaits finalization of changes to Germany's regulatory framework needed to ensure economic viability for H_2-ready gas-fired power plants and receiving all necessary permits. This is expected to take place in 2025 and the plant could produce power before the end of the decade, says RWE.

"This is the first GT36 turbine that could be installed in Germany. It is a great honor and privilege to be selected by one of the leading European utilities to be part of the country's decarbonization process" says Fabrizio Fabbri, CEO Ansaldo Energia.

"We are supplying our top-of-the-range engine with its unmatched operational flexibility, particularly in view of the unique sequential combustion to burn already today 50% (vol) hydrogen to support RWE in its ambitious plan to increase low-emission energy production".

test rig at DLR Stuttgart, capable of achieving sequential combustion conditions at small scale with good optical access (Figure 9).

This work is aimed at maximizing the outcome of the subsequent testing of the full-scale single-can combustor in the Ansaldo Energia atmospheric and high pressure rigs.

Via ***WP5*** the major power plant operator Edison will provide its perspective as GTCC operator, sharing its know-how in terms of operating parameters to enable Ansaldo development of the sequential combustion system for commercial operation of hydrogen-ready engines and power plants.

In this role, Edison will strongly contribute to the technology road mapping

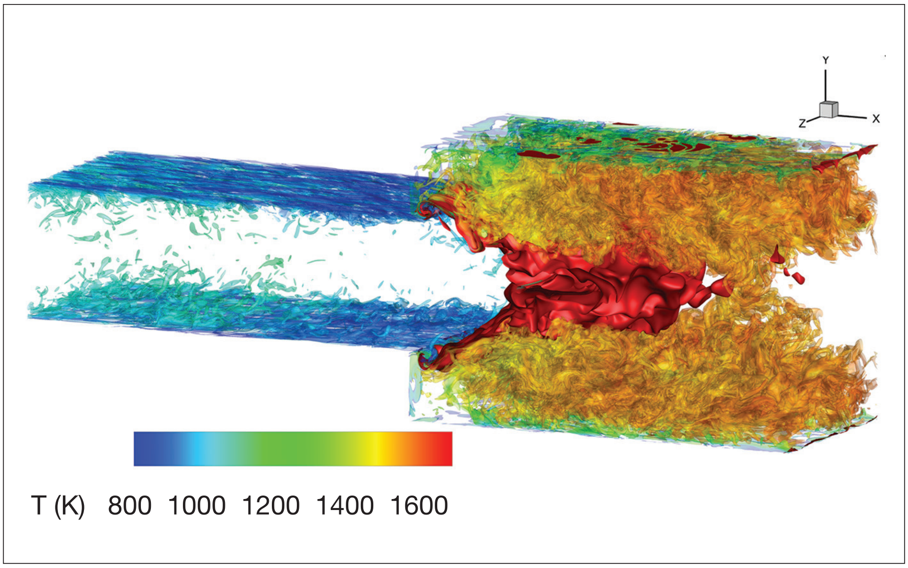

Figure 8. **Numerical simulation of hydrogen sequential combustion**. Latest analytical modelling and diagnostic techniques are being used to investigate static and dynamic flame stabilization. Results will support further analysis and testing with a focus on mitigation of thermoacoustic pulsation.

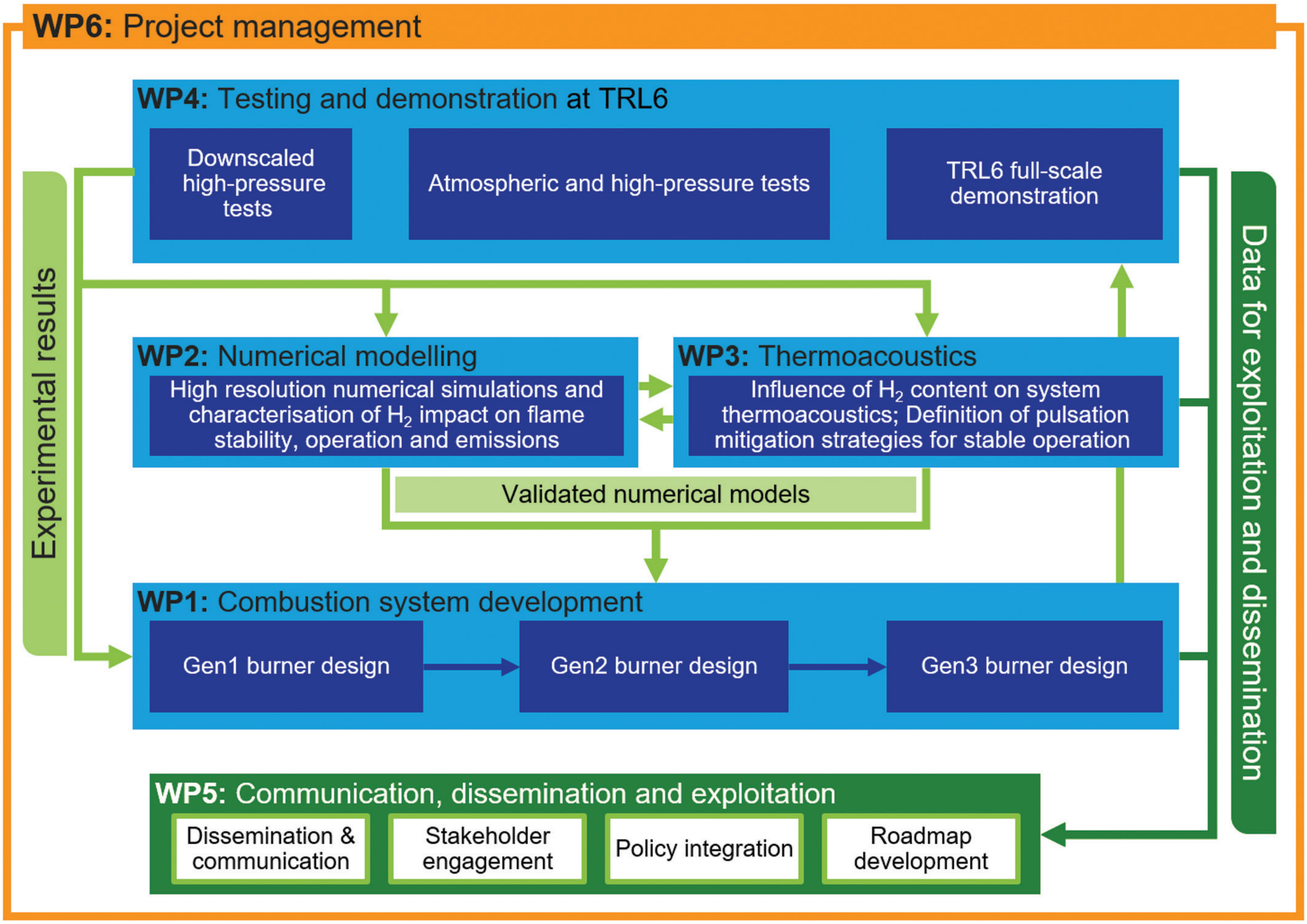

Figure 7. **FLEX4H2 work package structure.** Six interrelated work packages have been established. Project objective is to develop and validate (TRL6) a highly fuel- flexible CPSC combustor capable of operating with any hydrogen blend up to 100% H_2 by 2026.

regarding the uptake of the project results, while ETN Global will be responsible for the project's communications and dissemination activities.

ETN Global will also actively promote and facilitate stakeholder engagement with FLEX4H2 and integration of project outcome in the evolving EU policies.

Project Management (***WP6***), exploitation planning and IPR management will be supported by the specialized and experienced service provider ARTTIC Innovation GmbH.

Under this coordinated team approach the FLEX4H2 project is structured to present credible pathways for widespread exploitation of the project's results and provide the basis for a solid contribution to the EU Green Deal towards decarbonization of the electric power sector. ■

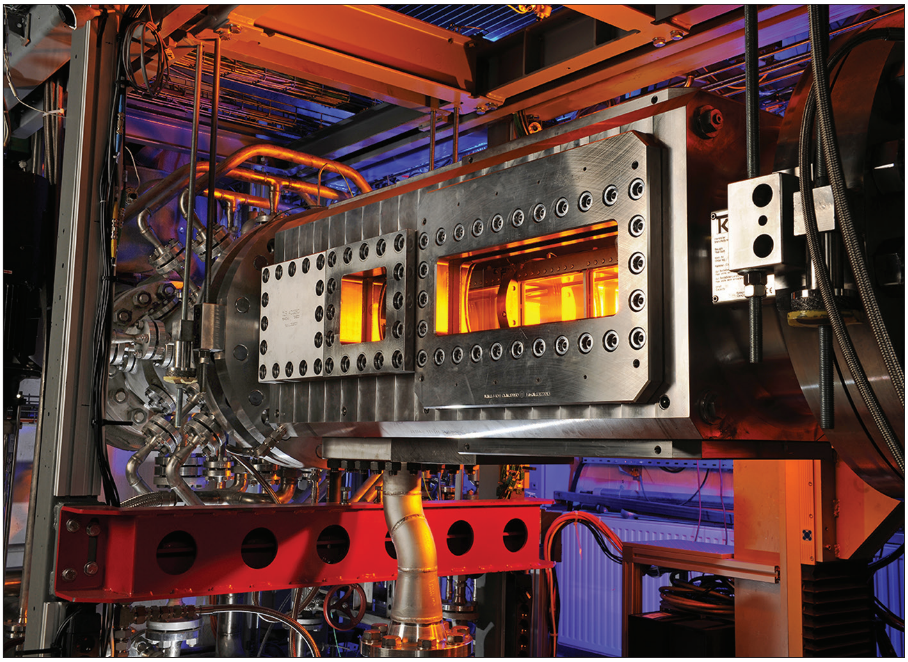

Figure 9. Optically accessible high-pressure sequential combustor rig. Small-scale testing at pressure (DLR, Stuttgart) is aimed at maximizing the outcome of subsequent testing of full-scale combustors in the Ansaldo Energia test rigs.

Note: The FLEX4H2 project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research (GA 101101427) and the Swiss Federal Department of Economic Affairs, Education and Research, State Secretariat for Education, Research and Innovation (SERI).

Clean Hydrogen Partnership

Co-funded by
the European Union

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

About the authors: Andrea Ciani is FLEX4H2 Project Coordinator and Manager, Hydrogen Combustion Technology at Ansaldo, Michael Düsing is Team Leader, GT Combustor Technology and Gerhard Früchtel is Combustor Department Head.

Acknowledgement: The authors extend their sincere gratitude to Vasileios Stefanis, Douglas Pennell and to the Ansaldo Energia combustor department responsible for developing the CPSC.