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HYFLEXPOWER: DEMONSTRATION PROJECT OF POWER-TO-H_2-TO-POWER ADVANCED PLANT CONCEPT

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ABSTRACT

Hydrogen combustion in gas turbines is expected to become a key technology for backing up intermittent renewable generation in deeply decarbonized energy scenarios. The HYFLEXPOWER project is the first-ever demonstration of a fully integrated power-to-H_2-to-power full scale pilot installation at an existing plant within an industrial facility in Saillat-sur-Vienne, France. This paper provides a comprehensive summary of the successful development, installation, and demonstration of the power-to-H_2-to-power application in the pilot plant: production of green hydrogen via an electrolyzer, storage of the hydrogen inside the plant and the re-electrification through combustion in a Siemens Energy SGT-400 gas turbine up to 30 vol.% hydrogen in natural gas. In addition, the technoeconomic feasibility of H_2 production, storage, distribution, and utilisation in the CHP plant was analysed and compared to the operation with natural gas based on current and anticipated energy market developments. The paper also provides an outlook on the next phase of the project to operate the pilot demonstration plant for carbon-free power generation with up to 100% hydrogen in 2023.

Keywords: Power-to-H_2-to-power; hydrogen gas turbine; pilot demonstration CHP plant; hydrogen; electrolysis; storage; decarbonization.

INTRODUCTION

Climate change has forced industry and governments to get serious about sustainable solutions that speed up the journey to reduce carbon dioxide emissions. In deeply decarbonized energy scenarios, hydrogen is expected to play a major role as key technology for storage of surplus renewable electricity on a large scale, and for fuel in gas turbines to back-up intermittent renewable generation.

One of the biggest challenges facing the widespread adoption of renewable energy sources (RES) is their intermittent nature and limited predictability, which can lead to mismatches between supply and demand on the grid. As the share of renewable energy in the electricity grid continues to grow, it becomes increasingly difficult to balance the intermittent supply with demand. This poses a significant threat to the stability of the electricity grids, highlighting the need for solutions to ensure the reliability and resilience of the grid in the face of this challenge.

While demand-side management can help handling these mismatches, supply management through power-to-H_2-to-power technology pathways can be used by utilizing excess renewable energy for conversion and storage of green hydrogen and providing backup power when it is needed.

Hydrogen fired gas turbine power plants are expected to play a key role in bridging the gap between the current and future energy technologies as they are considered the most reliable and cost-efficient technology to cope with the challenges of the fluctuating supply of renewable energy sources, particularly for large-scale power generation. Gas turbines can quickly ramp-up or down their power output to match the fluctuating supply of renewable energy sources, thus maintaining grid stability and reliability when the availability of renewable energy sources changes rapidly. In addition, gas turbines are a well-established technology with a proven track record of reliability and durability, utilized by virtually any kind of user (residential, commercial, or industrial). This makes them a dependable source of electricity in a renewable energy mix, especially during times when renewable energy sources are not available.

Numerous research and/or commercial projects on the topic of hydrogen production and utilisation have been developed in the past, both theoretically and experimentally. Most of these facilities were pilot or demonstration plants with power ratings under 1 MWe (Escamilla, et al., 2022). Recently, several industrial applications co-firing hydrogen at various levels in gas turbines with DLE combustion technology have been reported. Noteworthy is a Siemens Energy project with two SGT-600 gas turbines operating on 60 vol% hydrogen in DLE combustion mode keeping NOx emissions controlled to 25 ppmVd at a petrochemical plant in Braskem, Brazil (Elsner, 2022).

However, there are limited industrial power-to-H_2-to-power applications that are currently under development. The European Union's Horizon 2020 research and innovation programme has funded a few projects (European Commission 2023a, 2023b) including HYFLEXPOWER with concepts aiming the use of integrated gas turbine units either in a combined cycle power generation or cogeneration plants, where green hydrogen can be produced on site, compressed, and stored and later utilized in the gas turbine.

The challenges of operating gas turbine power plants on blends of natural gas and H_2 in a renewables-dominated grid are numerous. To gain real-world experience with new technologies in this environment, the EU funded HYFLEXPOWER project was launched in 2020 by a consortium of partners including Siemens Energy, Engie Solutions, Centrax, Arttic, German Aerospace Center (DLR), University College London, University of Duisburg-Essen, Lund University and National Technical University of Athens.

HYFLEXPOWER is the world's first fully integrated industrial power-to-H_2-to-power demonstrator in a real-world power plant application with an advanced high-hydrogen DLE gas turbine. The project's total budget is above 15 million €, of which 10.5 million € is funded by the European Union under the Horizon 2020 Framework Program for Research and Innovation.

This paper presents the development and implementation of the power-to-H_2-to-power advanced plant concept into an existing CHP plant located at the Smurfit Kappa recycled paper facility in Saillat-sur-Vienne, France. It provides details on the gas turbine package upgrade and on the high-hydrogen DLE combustion system development to allow operation with high-H_2 fuels in 2023. It further reports results achieved during the first demonstration campaign in the summer of 2022, the first-ever demonstration of the fully integrated power-to-H_2-to-power industrial scale power plant application, with up 30 vol.% H_2 in the gas turbine. Finally, a technoeconomic assessment is presented which investigates the economic feasibility of green H_2 production, storage, distribution, and utilisation in an integrated CHP unit, when compared to the conventional operation with natural gas.

NOMENCLATURE

ACE – Advanced Comb. System for High Efficiency
CAPEX – Capital Expenditure
CC – Cost of CO2
CCPP – Combine Cycle Power Plant
CEC – Clean Energy Center
CF – Capacity Factor
CFD – Computational Fluid Dynamics
CHP – Combined Heat and Power
CO_2 – Carbon Dioxide
DLE – Dry Low Emissions
ETS – Emissions Trading System
EU – European Union
GRI – Gas Research Institute
IR – Infrared
LES – Large Eddy Simulation
LCOE – Levelized Cost of Electricity
NG – Natural Gas
NO_x – Nitrogen Oxides
OPEX – Operational Expenditures
PEM – Proton Exchange Membrane
PPA – Power Purchase Agreement
R&D – Research and Development
RANS - Reynolds-Averaged Navier-Stokes
RES – Renewable Energy Sources
UV – Ultraviolet
WLE – Wet Low Emissions

POWER-TO-H_2-TO-POWER ADAVANCED PLANT CONCEPT

The solution is based on the storage of excess electricity via electrolysis of water and re-electrification of the produced hydrogen in an existing and upgraded thermal power plant. As demonstration pilot site, an industrial facility operated by Engie in Saillat-sur-Vienne, France was identified. The thermal power plant includes a Centrax CX-400 package installation with a Siemens Energy SGT-400 gas turbine core engine. The SGT-400 is a well proven small gas turbine of the Siemens Energy portfolio, used in power generation and oil and gas applications. The gas turbine power output for this application is up to 12 MW_{el} of electricity with the objective to supply energy in the winter season. To this end, a pioneering supply and storage concept for the site was developed and installed, supplying the consumer with electricity and heat from renewable energy sources. The system solution is realized on an industrial scale by the development, integration, and demonstration of innovative single components such as a Siemens Energy electrolyser, hydrogen storage, and a gas turbine package installation that will be upgraded with the aim of operating up to 100% hydrogen.

Error! Reference source not found. shows the HYFLEXPOWER power-to-H_2-to-power concept overview and Figure 2 shows an aerial view of the site in Saillat-sur-Vienne, France where the HYFLEXPOWER pilot has been built.

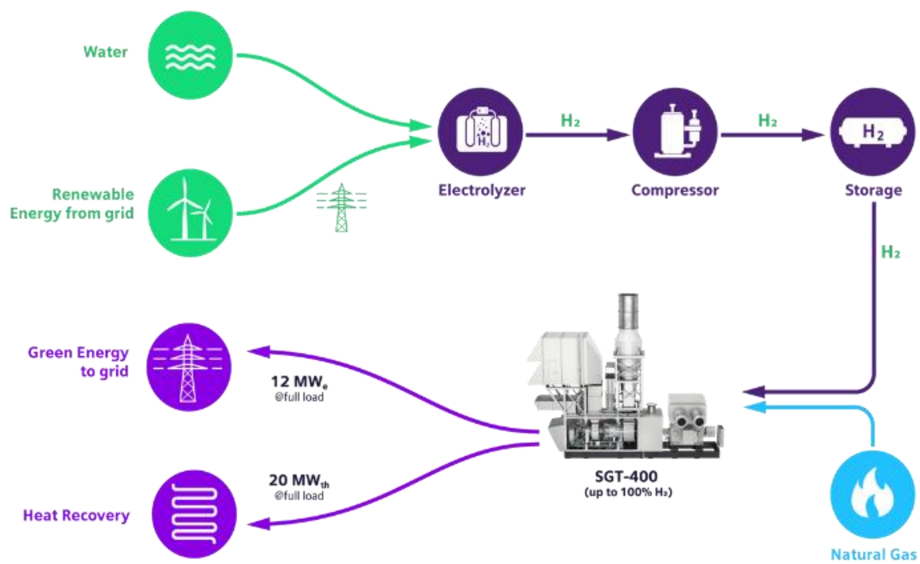

Figure 1: Power-to-H_2-to-power concept of EU funded HYFLEXPOWER Project.

Figure 2: Aerial view of Smurfit Kappa SGT-400 cogeneration pilot plant in Saillat-sur-Vienne, France.

Excess capacities from renewable energy sources on the grid, which arise on days with a lot of wind and sunshine and/or low consumption, are used for the electrolysis of water to generate green hydrogen. The resulting hydrogen is compressed and stored in pressurized tanks. The chemically bound energy in the hydrogen is then converted as needed in the SGT-400 gas turbine into electrical and thermal energy. The gas turbine package will be upgraded to allow varying feed from pure natural gas (the main component being methane – CH_4) to 100% H_2. Validation of the power-to-H_2-to-power concept including the gas turbine will take place in two experimental test campaigns with increasing H_2 content in the gas feed. The final goal is a validation with up to 100% H_2, demonstrating carbon-free energy production from stored excess renewable energy by project completion in 2024. The stored H_2 can then be used as a load component to compensate supply fluctuations in the power grid and for grid stabilisation. HYFLEXPOWER will demonstrate how the demand for electricity can be met at any time without CO_2 emissions, while at the same time ensuring grid stability. With the outlined concept a corresponding hydrogen-based solution will be demonstrated, which can be extended also on large-scale storage and re-electrification concepts. Wind power and photovoltaic generate CO_2 emissions-free electric current, which is primarily used directly by the consumer. Excess capacities in such a system – in contrast to today, where they either remain unused or production is curtailed – can be stably stored by transforming them into chemical energy using hydrogen electrolysis. Suited piping and storage tanks ensure that hydrogen is available for re-electrification in case of wind/solar lulls.

Hydrogen Generation, Storage and Supply System

A pioneering H_2 supply and storage concept for the site was developed and installed, that can supply the industrial site with electricity and heat from RES.

Electrolysis technology for the decomposition of water into H_2 and O_2 using electric current was implemented using a Siemens Energy proton exchange membrane (PEM) electrolyser. The PEM electrolyser (1 MW_{el}) has been manufactured according to the specifications for the conversion of excess RES power to chemical energy (H_2). The electrolyser is connected to a purification unit and hydrogen at the required specification for the overall application is generated: H_2 nominal production flowrate is 185 Nm^3/h at a pressure of 35 bar, with a purity > 99.995 %, and a temperature range between 2.5-75°C.

The pre-commissioning of the electrolyser was completed at the Siemens Energy facility in Mülheim an der Ruhr in Germany before delivery and installation at the demonstration site at Saillat-sur-Vienne. The associated deoxygenation (DeOxo) unit was also manufactured and was delivered at site as scheduled. A picture of the installed electrolyzer is shown in Figure 3.

A diaphragm compressor and piping system was installed to compress the generated H_2 up to 200 bar and transfer to the storage system.

Figure 3: Siemens Energy PEM Electrolyser.

A storage tank system composed of 348 bottles with a total volume of 57 m^3 and a pressure of up to 200 bar was designed and implemented to store the generated and purified gaseous H_2. The quantity of H_2 that can be stored in the storage tanks is approximately 950 kg and is sufficient to run the installed turbine at 100% load for 1 hour with pure H_2. Figure 4 shows a picture of the installed H_2 storage system.

Figure 4: H_2 storage system of the advanced plant concept.

A fuel mixing station was designed and implemented for the mixing and distribution of H_2 with natural gas to the gas turbine to produce electrical energy reducing CO_2 emissions. It can feed the turbine with stable and homogeneous fuel with a hydrogen content ranging from 0 to 100% H_2.

An in-depth safety analysis of the hydrogen pilot plant has been carried out involving detailed discussions and approvals from regional and national authorities prior to the start of the testing. Protection systems have been introduced and commissioned to continuously monitor the pilot plant and to ensure safe operation during production, storage, and re-electrification with hydrogen.

GT Package Upgrade

Centrax were responsible for the generator set upgrade to ensure safe operation with hydrogen fuel. The unit is CE marked for operating with natural gas, and the safety systems and fuel system were designed and certified for this purpose. The task involved the assessment of the risks associated with operation on hydrogen, and the mitigations required to ensure safe operation of the genset.

The areas of the package which required assessments and potential upgrades were the ventilation air system, the gas fuel module, the gas fuel detection and the fire detection and suppression system.

Ventilation System and Gas Detection

The ventilation system airflow was re-analysed using CFD analysis (Figure 5). The plots are for sections through the gas turbine enclosure with the ventilation air flowing from the left of the picture to the right. The contours show magnitudes of velocity which are used to determine gas cloud formations, locations, and dimensions for various operating conditions and failure modes for fuel ratios between 100% natural gas through 100% hydrogen. The information from the CFD was used to determine the following:

- **Enclosure integrity** – The results were used to determine that ventilation was sufficient to prevent formation of a gas cloud of a size that, if ignited, would exceed the design pressure limit of the enclosure.
- **Gas detection safety** – The size and location of the predicted leakage gas clouds helped determine the location of the gas detectors to ensure prompt detection and safe shut down before a hazardous situation could arise. Gas detectors were selected that could operate effectively on any blend of natural gas and hydrogen. The CFD analysis enabled definition of gas detection alarm and trip settings which take into consideration the different characteristics of the gases.

Fire System Risk Assessment

Centrax conducted a risk assessment to determine the requirements for the fire detection and the CO_2 suppression systems. The results from this assessment are as following:

- **Fire detection** – The flame detectors were replaced with combined IR/UV detection, which covers both hydrogen and natural gas applications.
- **Fire suppression** – Assessment as to the suitability of the existing CO_2 fire suppression system.

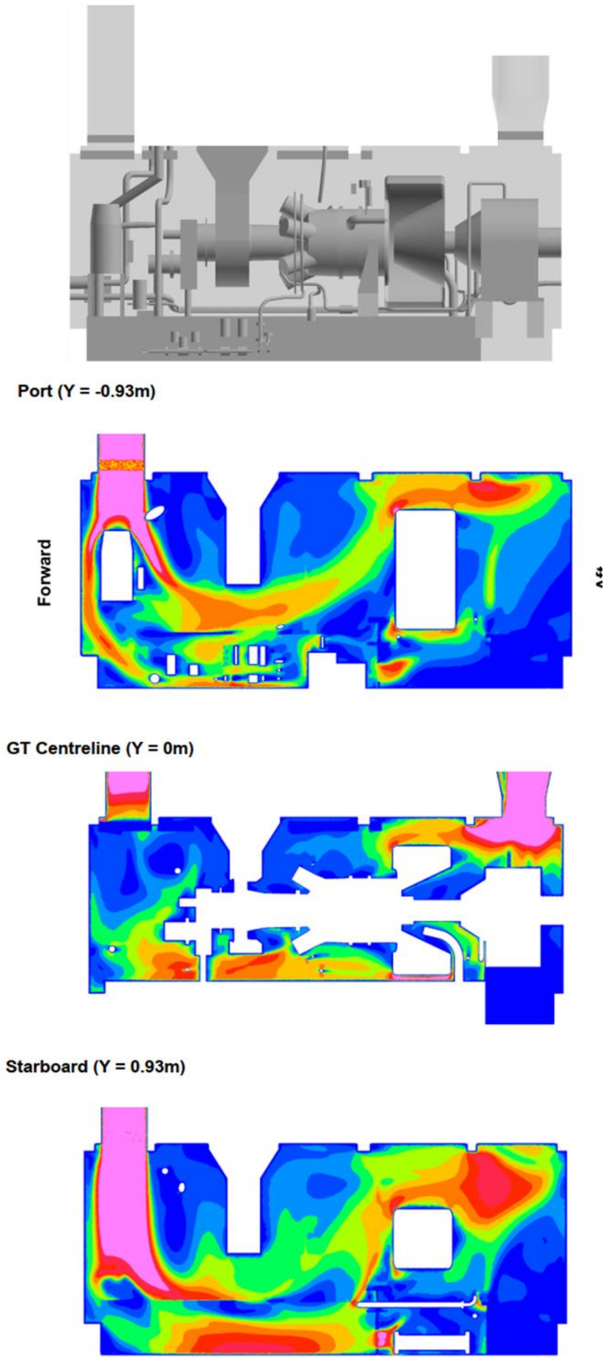

Figure 5: Result from CFD Analysis of the Air Flow.

Gas Fuel System Upgrade

Because hydrogen has a significantly lower density than natural gas, the volumetric flow to the engine needed to be increased to achieve the equivalent power output from the genset. To accommodate this increased flow, especially at higher percentages of hydrogen, Centrax worked closely with Siemens Energy to develop a new three-stream gas fuel system shown in Figure 6. The three-stream fuel system has independent fuel metering valves and allows precise delivery of fuel to the engine DLE H_2 combustion system.

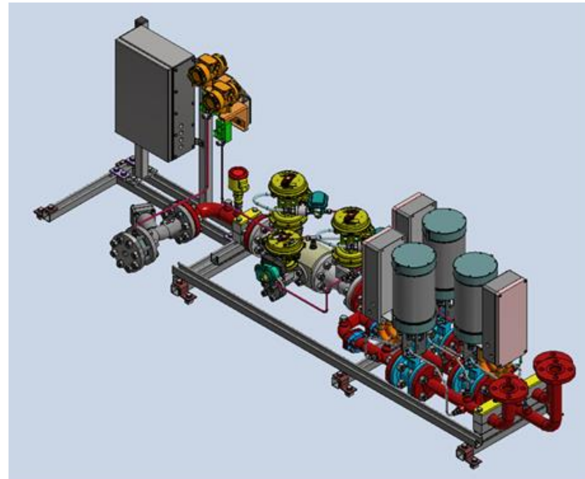

Figure 6: Centrax and Siemens Energy Three-Stream Gas Fuel Module.

Engine Monitoring System

Centrax collaborated with Siemens Energy, to develop a comprehensive monitoring system to maximise the useful data captured during the testing phase. There are approximately 200 pressure and temperature monitoring points on the engine, giving a comprehensive picture of the combustion process for assessment during and development after the test phase. A picture of the pressure monitoring system incorporated in the gas turbine package is shown in

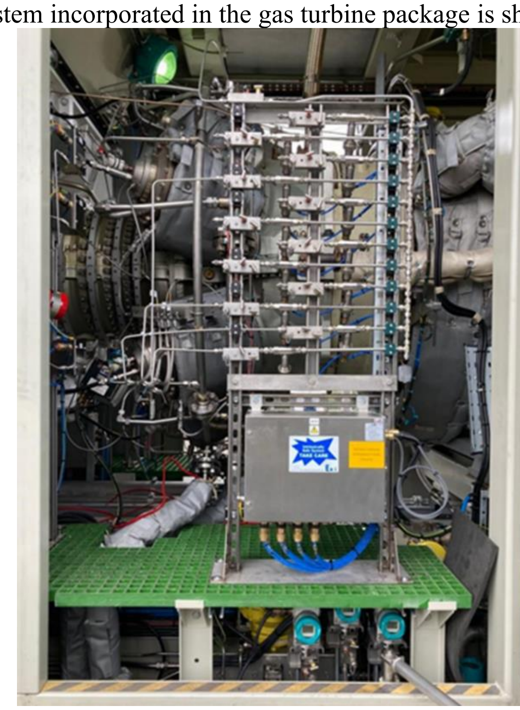

Figure 7.

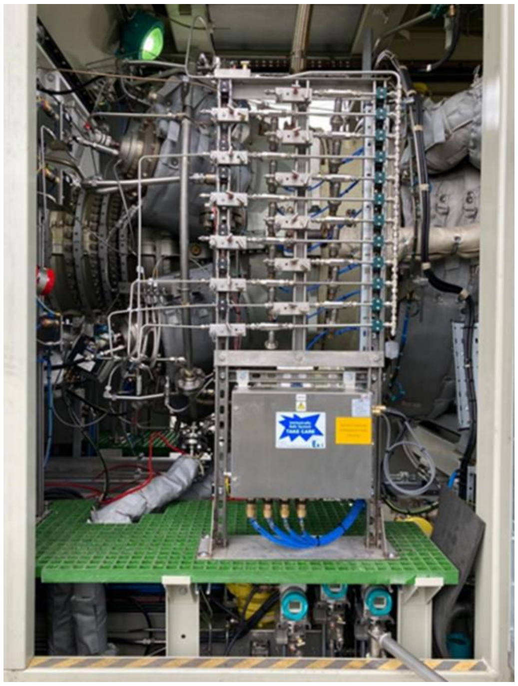

Figure 7: Pressure monitoring equipment installed on the gas turbine package.

DRY LOW EMISSIONS (DLE) HIGH HYDROGEN COMBUSTION SYSTEM DEVELOPMENT

To allow for an early commissioning and demonstration of the general functionality of the modifications at the Saillat-sur-Vienne power plant in summer 2022, a modified version of the standard SGT-400 natural gas combustion system was used. A sketch of the combustion system is shown in Figure 8. Changes were made to the location and geometry of the fuel injection holes, in both the main burner and pilot burner, to provide increased protection to flashback and reduce peak temperatures seen in the pilot burner.

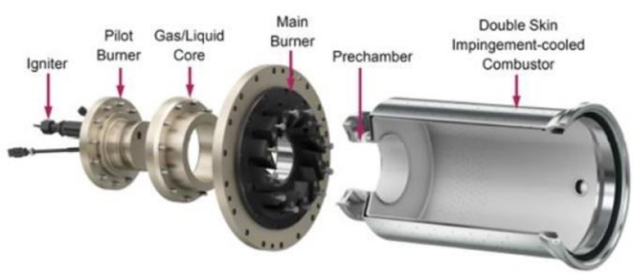

Figure 8: HYFLEXPOWER phase 1 (2022) combustor (expanded view).

Compared to natural gas, one of the primary challenges associated with high-H_2 combustion is the increased fuel reactivity characterized by an increased flame speed and reduced ignition delay time. The increased flame speed results in 1) a significantly increased risk of flashback in premixed combustion systems which can cause significant damage due to local overheating, 2) increased NO_x emissions due to the flame position moving upstream, and 3) a change of the thermo-acoustic response due to the change of the flame shape and location and, consequently, a change of combustion induced pressure pulsations, which potentially can lead to combustion system damage.

To address these challenges, Siemens Energy started the development of a new Combustion Technology Platform for combustion of hydrogen-natural gas blends with up to 100% hydrogen in dry low emissions (DLE) operation mode.

At first, a screening of chemical kinetic mechanisms for pure hydrogen was performed using LES as well as RANS CFD of a simple jet flame at gas turbine relevant boundary conditions. For comparison, the GRI 3.0 chemical kinetics mechanism established for natural gas was used as a baseline. From the study it was concluded that for hydrogen combustion simulations the choice of chemical kinetics mechanism appears to be of less importance than the treatment of turbulence and turbulence-chemistry interactions. For further information, including the investigated hydrogen mechanisms in the study, please refer to (Witzel et al., 2022).

Besides numerical simulations, combustion testing plays a crucial role in Siemens Energy's combustion development process. These combustion tests are typically performed at the Siemens Energy combustion test facility Clean Energy Center (CEC) in Ludwigsfelde near Berlin, Germany. The facility supports testing of components and systems for the Siemens Energy gas turbine portfolio – from large gas turbines down to small industrial designs – and allows for a wide variety of fuels to be tested. In 2019, hydrogen testing capability was added to CEC to ensure that it can support the increased demand of hydrogen applications. A picture of the hydrogen trailers and the H_2/NG mixing station is shown in Figure 9.

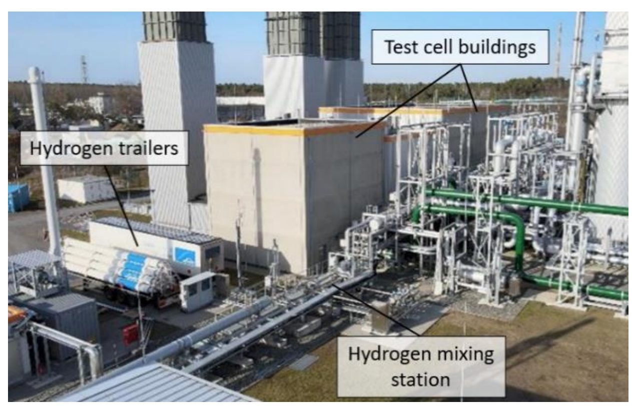

Figure 9: Hydrogen test setup at the Siemens Energy combustion test facility Clean Energy Center (CEC).

The main components of the new combustion technology are a jet-stabilised main burner with multiple injector/premix passages, a central swirl stabilised pilot burner, and an axial fuel stage. This combustor architecture is similar to the latest ACE combustion technology introduced with Siemens Energy's 9000HL product family (Krebs et al., 2022).

Meanwhile, more than 20 variants and design iterations of the new combustion technology were tested in five test campaigns at CEC. A main objective of each of the tests was the investigation of the flashback limits for the different hardware variants. For these tests, the H_2 content was increased to 100% at a low firing temperature followed by a stepwise increase of the firing temperature until flashback occurred. This test procedure was repeated at different thermodynamic boundary conditions including different pressure levels as well as flow velocities. The flashback events were detected with both thermocouples at the premixing passages as well as with a video camera. The most promising variants showed sufficient flashback margin with 100% H_2 at SGT-400 gas turbine operating conditions. For the HYFLEXPOWER engine test, it is expected that the margin may reduce when the burner is operated in a full engine configuration compared to the well-controlled test rig. In this context, the HYFLEXPOWER engine test in 2023 (phase 2) will provide very valuable information to establish a rig-to-engine correlation for the newly developed hydrogen combustion technology.

After successful demonstration of the combustion technology in the HYFLEXPOWER project, it is planned to scale and adapt the technology platform to other frames of the Siemens Energy gas turbine portfolio. For further information on the 100% hydrogen combustion technology development please refer to (Witzel et al., 2022).

POWER-TO-H_2-TO-POWER DEMONSTRATION AND RESULTS

The demonstration core engine for the phase1 testing in 2022 was built at the Siemens Energy facility in Lincoln. This is a standard SGT-400 13 MW gas generator apart from the modifications to the combustion system as described above, to deal with the different gas properties for a H_2 fuel blend with natural gas. Additional instrumentation was added during the build to provide better insight into the behaviour of the turbine when operating at site. This included thermocouples for detection of flashback, combustion can dynamics sensors and additional differential pressure transmitters.

Before shipment to Saillat-sur-Vienne, the gas generator underwent an extensive works test on natural gas to establish a baseline performance and to check the instrumentation was providing good signals to the data logger. After installation at site the gas turbine was commissioned during June 2022 on natural gas. Engine controls set-up points were adjusted, and the combustor pilot/main fuel split was mapped over the operating range up to 100% load.

Once all components of the integrated plant had been commissioned it was possible to introduce H_2 blended with natural gas, into the gas turbine. In order to validate the quality of the signal from the flow meter for H_2, some additional checks were carried out:

- Monitoring the storage pressure and comparing the calculated H_2 consumption with the integration of the flow meter over a fixed period.
- Comparison of the measured CO_2 reduction with calculated reduction based on the measured H_2 levels.
- Thermodynamic modelling of the gas turbine using measured pressures and temperatures to show difference in characteristics are consistent with the changes in fuel composition.

All methods provided consistent results and gave confidence in the values from the flowmeter, as well as providing a valuable cross check on the quality of signals from other instrumentation used in the calculations.

The gas turbine was operated with progressive increases in the H_2 content of the fuel and engine loading in order to explore limits of operation. Some adjustments of combustor tuning parameters were made during the course of testing in order to maximize the flow of H_2 that could be extracted from the storage. Peak flow was about 120 kg/hour of H_2, which was achieved with a hydrogen blend of 30 vol. % and gas turbine load of approximately 90%.

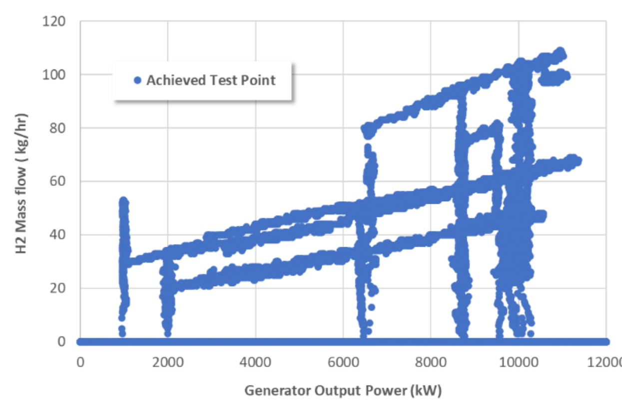

Figure 10: Operating envelope of generator power with hydrogen flow rate.

Figure 10 illustrates the operating envelope covered during the period of the testing. Each point represents a logged dataset showing the power on the x-axis and the mass flow of hydrogen on the y-axis. The clusters of points arranged in vertical lines are sweeps at fixed load with varying H_2 blend from 0 to 30 vol.%. The clusters that form lines from left to right, are sweeps through the load range with fixed H_2 blend (vol. %). The topmost line, from a load of 6,500 kW to 11,000 kW represent test points at a fuel blend of 30 vol.% H_2.

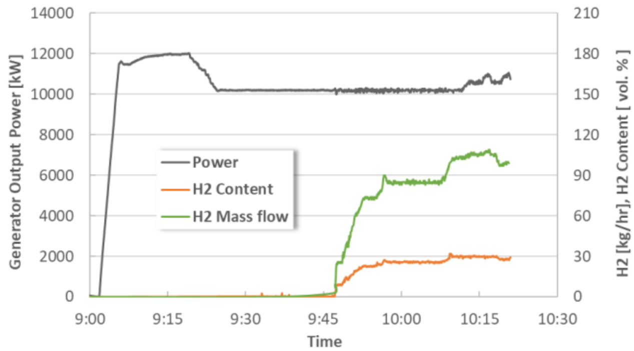

Figure 11 shows a representative test run for different load and H_2 variations during the test. Here test points with11,000 kW generator output power and 30 vol.% H_2 in the fuel blend are reached in the last 15 minutes of the test.

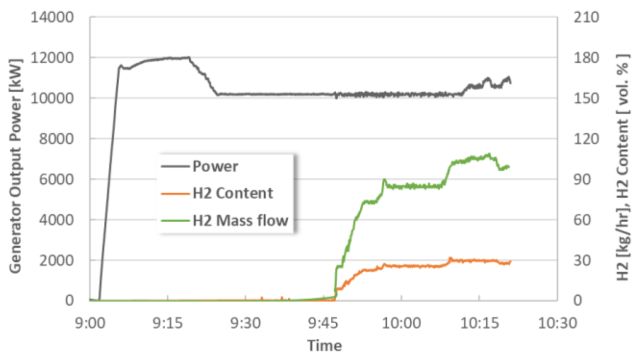

Figure 11: Test run of the advanced plant concept with H_2 containing fuel.

Engine testing was conducted with and without bleed control. Bleed of air from the centre casing of the gas turbine is used to maintain combustor firing temperatures when operating at part load, to maintain complete combustion of the fuel and avoid the production of CO above local regulatory limits. At full load, the NO_x emissions increased for 30 vol.% H_2 blend relative to natural gas as expected, although still below the target of 15 ppmVd. Due to constraints on test time, it was not possible to complete the necessary mapping to optimise emissions over the wider load range, although the results suggest this is achievable.

During testing, component temperatures and combustor dynamic pressures were taken in addition to the emission levels and captured in the data logger. Results demonstrated that there was a good agreement with the single can tests conducted on this combustor geometry in the high-pressure combustion testing facility in Lincoln, UK. This gives confidence in future development for the combustor using single can tests. Performance of the demonstrator engine had been matched with a performance model and showed very good alignment when running on natural gas and blends up to 30% H_2. It is concluded that levels up to 30% H_2 has very little performance impact on the engine.

The core engine was stripped and inspected at the end of testing, and it was determined that apart from the new combustor module that is in development for 100% H_2 operation, all other parts could be reused.

TECHNO-ECONOMIC ANALYSIS

A technoeconomic evaluation of the HYFLEXPOWER solution was conducted in order to investigate the economic feasibility of onsite H_2 production, storage, distribution, and utilisation in a commercial CHP plant (Skordoulias et al., 2022). The effect of various technical and energy market parameters in the Levelized Cost of Electricity (LCOE) of the integrated CHP plant for H_2 mixtures up to 100% was investigated and compared to the operation with 100% natural gas.

The life of the CHP unit including the H_2 production, storage and distribution system was considered 20 years. The PEM electrolysis stack is assumed to be replaced after 80.000 h of operation. The CHP is covering the thermal demands of an industrial site, but it is assumed to offer power to the grid, so cost of CO_2 emissions (CC) is attributed only to the electricity production for the calculation of the LCOE. The operation period of the cogeneration unit was set equal to 151 days per year, i.e., 3624 h/year accounting for the heat demand and availability.

Based on the installed capacity of the CHP unit and its operational hours, the required amount of hydrogen was calculated based on the different H_2 substitution scenarios. The PEM electrolysis system is powered by 100% renewable electricity, proven by green Certificates of Origin, based mainly in intermittent (wind, solar) or continuous (biomass) renewable energy power, with a constant fixed price of electricity regulated by a Power Purchase Agreement (PPA) between the RES Aggregator and the Plant Owner.

The main assumptions and factors for the investment expressed as Capital Expenditure (CAPEX), for the operational expenditures (OPEX) and natural gas, power and carbon prices are presented in Table 1.

Table 1: Assumptions for the economic analysis of the power-to-H_2-to-CHP system components.

Parameter	Reference Year 2022	Reference Year 2030
CAPEX PEM Electrolysis System (including compression and storage) (€/KWe,in)	1500	800
Replacement Cost Stack (Stack lifetime 80.000 h of operation)	30% $CAPEX_{PEM,\ ES}$	30% $CAPEX_{PEM,\ ES}$
Cost of Water (€/m^3)	3.8	3.8
Cost of Electric Power (€/MWhe,in)	40	40
Scaling factor	0,9	0,9
Annuity (%)	8	8
OPEX PEM Electrolysis System (€/MWhe,in)	3	3
PEM Electrolysis System Maintenance Cost	2% $CAPEX_{PEM,\ ES}$	2% $CAPEX_{PEM,\ ES}$
Cost of CO_2 (€/t)	90	150
OPEX Open Cycle Gas Turbine (€/MWhe)	4	4
Cost of Natural Gas (€/MWhth)	90	90

The results of the LCOE with carbon cost attributed to power generation for various hydrogen substitution ratios (based on thermal-energy substitution) and CFs are presented in Figure 12 and Figure 13.

Based on this analysis for year 2022, although the unit's CO_2 cost, as regulated by the EU ETS system, increases the cost of generating electricity for low H_2 substitution rates, it does not compensate for the additional expenses required for the expansion of infrastructure for green H_2 production storage and distribution. Based on the current economic, technological and market developments it is not yet economically viable to utilize hydrogen in the cogeneration unit compared to the operation with natural gas. However, based on the analysis in year 2030, as electrolyser costs have already been reduced by 60% in the last ten years and are expected to further halve in the near future due to the R&D advancements and increased market maturity, green hydrogen utilisation in the cogeneration unit appears to be a more economically viable business case compared to operating with natural gas almost for all electrolyser capacity factors (CF>30%) and H_2 substitution ratios (>10%). Moreover, the carbon cost is expected to increase further in the coming years in the effort to decarbonize the EU energy system as also described above, leading to a further increase in the levelized cost of electricity for units using fossil fuels, making the green hydrogen utilisation business case even more economically viable.

The break-even point for green hydrogen utilisation in cogeneration plants to be economically viable compared to 100% natural gas firing can be achieved mainly through high natural gas (> 90 €/MWh_{th}) and even with low EU ETS Carbon prices (~ 20 €/tCO_2). Overall, with the increase on the natural gas and CO_2 emission costs, the substitution of hydrogen in the proposed unit leads to lower LCOE values, making profitable the integration of green hydrogen in existing cogeneration units.

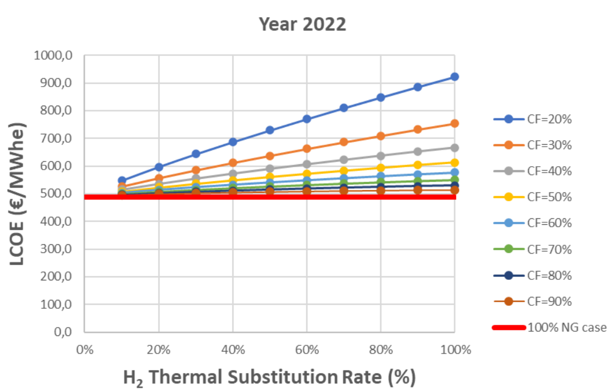

Figure 12: Levelized Cost of Electricity (€/MWhe) as a function of CF and H_2 thermal (energy) substitution ratio Reference Year 2022.

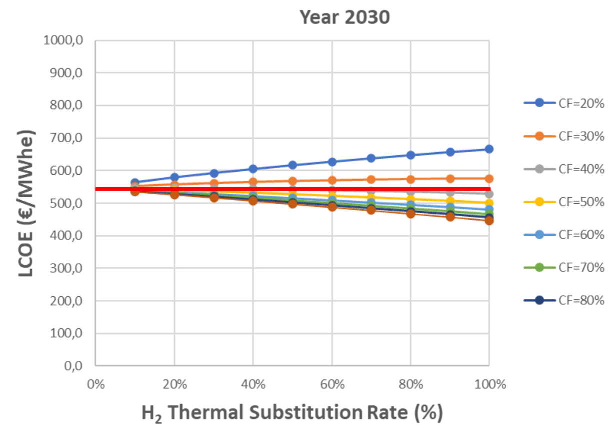

Figure 13: Levelized Cost of Electricity (€/MWhe) as a function of CF and H_2 thermal (energy) substitution ratio Reference Year 2030.

Moreover, the proposed unit can access further profits, by selling the produced oxygen and/or waste heat as well as medium and high-pressure steam in the district heating network instead of the industry.

The technological scheme suggested is also relevant to the Complementary Delegated Act of EU taxonomy covering sustainable technologies and imposing thresholds for their characterization. Especially gas fired plants will need to burn a share of at least 30% hydrogen or biogas from 2026 and at least 55% from 2030, while sustainability thresholds are revised to 100 g CO_2/kWh_e threshold in case a plant with lower emissions is replaced and to 270 g CO_2/kWh_e threshold otherwise.

CONCLUSION

The design and construction of an advanced plant concept with H_2 generation, storage, supply, mixing and re-electrification has been successfully completed. Following the modifications at the existing CHP plant in Saillat-sur-Vienne, France, HYFLEXPOWER has delivered the first-ever running demonstration of a fully integrated power-to-H_2-to-power industrial scale power plant application. Results for the first testing period during summer 2022 have included gas turbine operation with up 30% H_2 blend with natural gas by volume.

In parallel to the site activity, the development of a high-hydrogen DLE combustion system capable of operation with 100% H_2 has been progressing. Rig testing at relevant gas turbine boundary conditions has been achieved, and the developed technology is to be uploaded into the demonstration core for the upcoming site testing with high-H_2 fuels in 2023.

A technoeconomic assessment in terms of LCOE was conducted in order to investigate the economic feasibility of green H_2 production, storage, distribution, and utilisation in an integrated CHP unit compared to the conventional operation with natural gas. Simultaneous decarbonization of power and heat production, via the power-to-H_2-to-power solution is achieved and presenting a viable business case only for decreased CAPEX of the PEM electrolysis system and secured low power prices for H_2 production (≤50 Euro/MWh). Overall, with the increase on the natural gas and CO_2 emission costs, the substitution of hydrogen in the proposed pilot plant leads to lower LCOE values, making the integration of green hydrogen in existing CHP units viable.

The construction and operation of the integrated pilot plant is providing valuable information on the technical, safety and economic constraints for advanced power-H_2-power systems. This understanding will be further developed following testing of up to 100% H_2 in the summer of 2023.

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