H_2-IGCC FINAL PUBLISHABLE SUMMARY

1 November 2009 – 30 April 2014

PROJECT PERIODIC REPORT

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1. Final publishable summary report

1.1. Executive Summary

Following the overall objective of the H2-IGCC project which was set to be “to provide and demonstrate technical solutions, which allow the use of state of the art high efficient, reliable gas turbines in next generation IGCC plants, suitable for combusting undiluted hydrogen-rich syngas derived from a pre-combustion CO2 capture process with high flexibility”[1] were the main objectives achieved in highly integrated activity across all work packages.

The overall system was thermodynamically optimised based on state of the art technology and requirements with a process integration level satisfying practical operational needs and experiences of the plant operators involved. Furthermore was the dynamic behaviour of the system evaluated, with special focus on its capabilities for fast transients to cope with the increasing share of fluctuating renewables in the grid. The thermal and economic performance of the cycle was evaluated and benchmarked with competing cycles such as the supercritical steam and combined cycles.

Development based on an existing state of the art gas turbine resulted in a version optimised for use of hydrogen rich syngas as main fuel. Mainly impacted were the compressor aerodynamics as well as the flow path and cooling system of the turbine. Within the compressor it was possible to maintain a reasonable high surge margin to allow for changes in cooling flow extractions and increased fuel flexibility. Using clean syngas will be possible only with major compromises in design due to the significantly increased volume flow into the turbine.

Due to the use of new fuel produced from gasification of coal and its resulting impact on impurities in the hot gas entering the turbine were the consequences for turbine balding and coating evaluated and tested / verified. The test rig used for materials and coating testing operated with a representative flue gas composition and temperature, thus providing the environment to reliably prove the concepts developed during the project. It was specifically designed and adjusted to meet the tight requirements of the project.

Very intensive evaluation of the combustion process for undiluted, hydrogen rich, premixed type of combustor covered model development, numerical simulation as well as verification of the models and concepts in different levels of detail. Included were detailed and basic investigations on the combustion as well as more applied evaluations and tests targeting design issues of a real premixed type of gas turbine combustor. The results indicate that using the same combustor for hydrogen-rich fuel and / or natural gas might be most likely not possible.

Results of the project are published and made available in several papers and reports. Even though IGCC plants might not be economically competitive in the very near future several results of the project can be used for other applications, especially when it comes to the results of the more basic research in combustion, materials, turbomachinery and the systems analysis and techno-economical evaluation.

[1] Project Summary form «Low Emission Gas Turbine Technology for Hydrogen-rich Syngas», EU FP/-Project Number 239349

1.2. Project context and objectives

Concept

The continued need to use coal as primary fuel combined with requirements to curb CO_2 emissions generate a genuine demand for the development of reliable, low-emission, cost-competitive gas turbine technologies for hydrogen-rich syngas combustion.

Integrated Gasification Combined Cycle (IGCC) is currently one of the most attractive technologies for the high-efficiency use of coal. It enables the conversion of coal and other solid or liquid fuels to a gaseous syngas fuel, while still maintaining aggressive emissions targets and high efficiency. **Pre-combustion methods are the preferred means of capturing CO_2 in IGCC systems.** An IGCC plant equipped with pre-combustion CO_2 capture combined with low emissions of other gases, e.g. NO_x, $SO_{x,}$ can be realised through major advancement in IGCC gas turbine technology.

In a typical IGCC plant, coal is converted to a synthetic fuel gas (syngas) in the gasifier. At the exhaust of the gasifier, the syngas is a mixture of mainly hydrogen (H_2), carbon monoxide (CO), CO_2 and steam. After cooling, contaminants, such as particulates, hydrogen sulphide and hydrogen chloride, are removed in a number of gas cleaning stages. In existing IGCC plants, diffusion burners are applied on the gas turbines; as the reactivity of hydrogen is much higher than that of natural gas, it is complicated to apply pre-mix burners (Dry Low Emission of Dry Low NO_x burners). As a result of the higher adiabatic flame temperature, the syngas is diluted with nitrogen or water/steam to reduce the formation of NO_x. Downstream of the gas turbine, NO_x emission can also be reduced further by means of a Selective Catalytic Reduction (SCR) unit. In current IGCC plants, the gas turbine exhaust is fed to a Heat Recovery Steam Generator (HRSG). Steam from this HRSG is used to drive the steam turbine. Currently net electrical efficiencies up to 45 % have been achieved.

The use of gasification technology makes it possible to remove carbon dioxide upstream the burners. After contaminant removal to a high standard, the CO in the syngas is shifted to CO_2, by the injection of steam in a catalytic shift converter, leaving the syngas with an increased level of H_2 in combination with CO_2, and any remaining trace species. The CO_2 can then be separated from the gas mixture using physical solvents, or in the future membranes, prior to further clean-up, compression and transport to a suitable underground storage location. **This pre-combustion Carbon Capture and Storage (CCS) is a very promising technology.**

Existing assessments suggest that there is around a 7 - 10% reduction of cycle efficiency due to CO_2 capture and indicate strong dependence on the fuel and selected cycle. Parameters influencing the thermodynamic efficiency of gas turbine-based processes include cycle pressure ratio, maximum allowable turbine inlet temperature and hot gas path cooling demand, as well as the required purity of CO_2 and O_2 (used in the primary fuel gasification process step).

At the moment, combustion of hydrogen-rich syngas derived from coal in gas turbine is not feasible with low NO_x premix systems. Current gas turbine technology for power and heat generation is generally optimized for natural gas.

The inherent variability in composition and heating value of syngas provides one of the largest barriers towards its usage. These are recognised disadvantages of the current technologies for syngas combustion which increase the costs of plant operation. **Very high flow rates of cost-intensive dilution gas (N_2, H_2O) are needed to combust syngas in highly-diluted diffusion flames, and to control NO_x emissions.**

A representative nitrogen-diluted syngas fired in the turbine combustor at one IGCC plant contains about 53 % N_2 for dilution with about 11% H_2 and about 4% H_2O[2]. A representative steam-diluted syngas fired in the turbine

[2] CRE Group Ltd., "Migration of Gas Turbine Problems and Performance for Biomass IGCC: Experiences in Europe and US. Lessons Learnt for Coal IGCC", CRE Report No. 7996/3, April 1999

combustor at another IGCC plant[1] contains 22% H_20 and 28% H_2 (all of the above are expressed as volume %). Consequently, the diluents used (steam v. nitrogen) and water vapour formed from H_2 in the combustion process along with differences in water input for various gasification processes (e.g. dry feed v. wet feed) result in significant differences in water vapour levels in the combustion gases flowing through IGCC turbine hot sections. This can result in differences in hot section component degradation since increased water vapour levels have increased oxidation rates in laboratory tests of turbine materials[3]. Syngas turbine inlet temperature is also an important operational factor affecting materials performance.

In addition, de-rating of the gas turbine has been essential to avoid overheating of turbine components, due to the high flow rates and steam contents of the combustion gas. **The low reliability and availability of the gasifier, the low cycle efficiency due to reduced firing temperatures, and the necessity of fuel pre-treatment increase the operational costs of an IGCC plant compared to a natural gas combined cycle plant.**

As Carbon Capture and Storage (CCS) technology is identified by the European Strategic Energy Technology Plan (SET-Plan) as one of the promising technologies endorsed by the European Commission in reaching the goal of 20% CO_2 reduction by 2020, implementation by industry partners of the technical solutions developed in this project will eventually allow for the deployment of high efficiency gas turbines in competitive IGCC plants using undiluted syngas with CCS by stakeholders at a competitive commercial scale, with the target year 2020.

Overall Objective and Vision

The overall objective of this project is to provide and demonstrate technical solutions which will allow the use of state-of-the-art highly efficient, reliable gas turbines in the next generation of IGCC plants, suitable for combusting undiluted hydrogen-rich syngas and also allowing for high fuel flexibility. It is required to minimize the impact of introducing carbon capture systems on the overall efficiency IGCC power plants. The performance of the gas turbine is of particular importance in maximizing the efficiency and performance of any form of IGCC plants. Also, the total plant power output and hence the cost per MW is determined by the optimum combination of state-of-the-art gasification and gas turbine units, at an appropriate level of integration.

In order for industry to invest in the next generation of IGCC plants with CO_2 capture systems, both the technical and commercial risks need to be quantified and minimized, specifically those associated with the gas turbine. Further, the viability of the required technical solutions developed through OEM/Utility sub-system/component trials needs to be fully demonstrated before they can be deployed with confidence.

At the current state-of-the-art, very high flow rates of cost-intensive dilution gas (N_2, H_2O) are needed to combust syngas in highly-diluted diffusion flames, and to control NO_x emissions. **Minimizing and/or eliminating the dilution of syngas and implementing current state-of-the-art gas turbine technology are the first steps towards higher efficiency IGCC plants.** To date, the most advanced IGCC systems have used an old generation of gas turbines giving a net efficiency in the range 43 – 45%, while with the application of G- or H- class gas turbines, the net efficiency is expected to increase to 48 – 50%. These values are comparable to or higher than those typical of the most advanced ultra-supercritical (USC) pulverized coal power plants operating in regions with advantageous environmental conditions. Moreover, the expected efficiency reduction for implementing CCS will be smaller for IGCC plants than for USC plants.

Thus, this project will provide solutions to the technical challenge of burning undiluted syngas in a safe and reliable way, with efficiency and NO_X emissions similar to state-of-the-art gas turbines fuelled by natural gas (η>38% in open cycle with NO_X < 25 ppm at 15% O_2). In addition, high fuel flexibility will be demonstrated in order to allow the burning of back-up fuels, such as natural gas, without adversely affecting the reliability and availability. This is an important operational requirement to ensure optimum use of the gas turbine.

[3] Onal, K., Maris-Sida, M.C., Meier, G.H. and Pettit, F.S., "The Effects of Water Vapor on the Oxidation of Nickel-Base Superalloys and Coatings at Temperatures from 700°C to 1100°C", pp. 607-616 in Superalloys 2004, K.A. Green, H. Harada, T.W. Howson, T.M. Pollock, R.C. Reed, J.J. Scherra and S. Walston, editors, TMS, September 19, 2004

The project is divided into 5 Subprojects (SP):
SP1 Combustion
SP2 Materials
SP3 Turbo-machinery
SP4 System analysis
SP5 Management

An overview of the Subproject (SPs) is shown in the graph below:

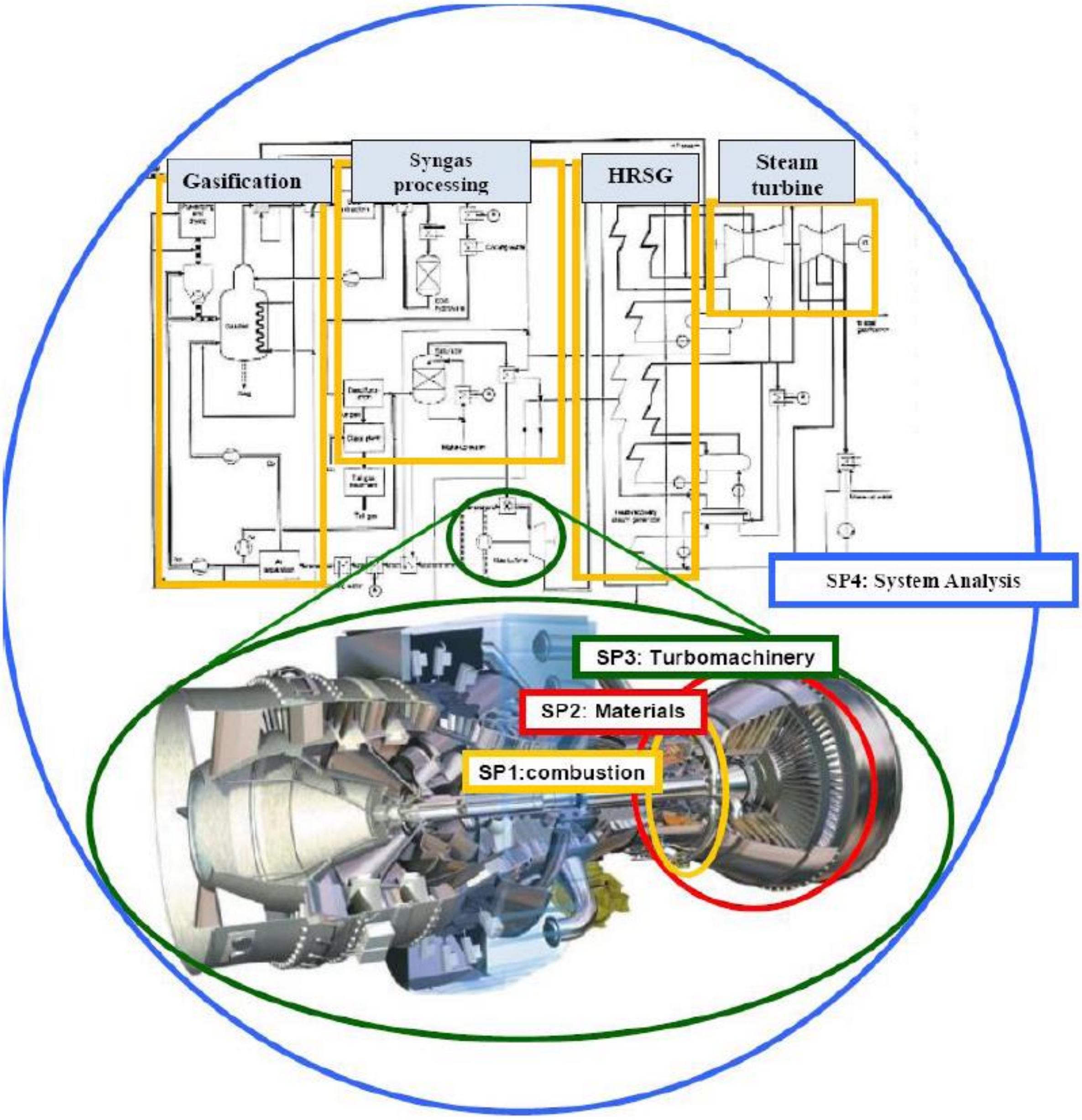


Figure 1 - Subprojects Overview

The following initiatives are required to reach the goals of the project:

- **SP1: Safe and low emission combustion technology for undiluted, hydrogen-rich syngas will be developed and demonstrated**. In order achieve this, problems created by differences between the combustion properties of hydrogen and natural gas need to be addressed and solved. These differences include higher flame speed, higher adiabatic flame temperature, drastically reduced auto-ignition delay times and the large increase in volumetric fuel flow rate of hydrogen compared to natural gas.

- **SP2: Improved materials systems** with advanced coatings able to protect base blade and combustor materials against the different and potentially more aggressive temperatures and compositions of exhaust gases will be developed and demonstrated. In particular, hot corrosion and high temperature oxidation of corrosion resistant coatings and bondcoats and sintering/solid particle erosion of thermal barrier coatings will be considered. To assess the components integrity and degradation kinetics during operation, advanced NDE&T (Non Destructive Evaluation and Testing) will be developed. Simulation tools for estimating performance and lifetime of materials systems will also be enhanced to suit the new operating environments.

- **SP3: Modified compressor/turbine aerodynamics and hot path cooling** will be investigated in order to deal with the increased mass flow rate of fuel and the increased heat transfer of exhaust gases. This is particularly important because;

1. the increased fuel mass flow rate could lead to compressor instability and turbine vibration;
2. the higher specific heat of the exhaust gases will lead to increased operating temperatures of the hot gas path components in comparison with natural gas-fired gas turbines.

- **SP4: Thermo-economic system analysis** will evaluate optimum IGCC plant configurations with special emphasis on the power island system components, including multiple train arrangements. Guidelines for an optimised full scale integration and operation of gas turbine will be defined. In particular, the compatibility of the combustion technology with the materials and turbo-machinery requirements will be optimised. To minimise operation and maintenance costs, the integration of enhanced lifetime modelling of components within the overall gas turbine control system will also be considered.

The vision of the project is to enable the application of state-of-the-art gas turbine technology in the next generation of IGCC plants with the flexibility to operate with H_2-rich syngas after the introduction of CCS.

1.3. Main S&T results/foregrounds

SP1 – Combustion

1. General information and combustion fundamental background

The technical background for the combustion demonstration activities (which are prominently covered in this Publishable Summary Report) has been accomplished by extensive project activities aimed at widening the knowledge space on fundamental combustion properties (ignition delay time, laminar/turbulent flame speed, chemical kinetics for heat release & emissions) of H2-rich fuel mixtures.
With the combined effort of generating validation data in dedicated combustion experiments and performing chemical kinetic modelling studies to proof the validity of elementary reaction mechanisms, the project partners (NUI, DLR, TU/e, PSI) were able to improve the knowledge base for H2-rich fuel mixtures at gas turbine relevant combustion conditions in a significant way. Both, ignition delay times and laminar burning velocities could be predicted well with a reaction mechanism formulated by the project consortium. Some of the validation data generated are first-of-its-kind data for the conditions of interest (high H2 content fuels; elevated pressure; elevated initial temperatures). Examples of these results are shown in Fig. 1-3; more details can be found in the annual reports of the project.

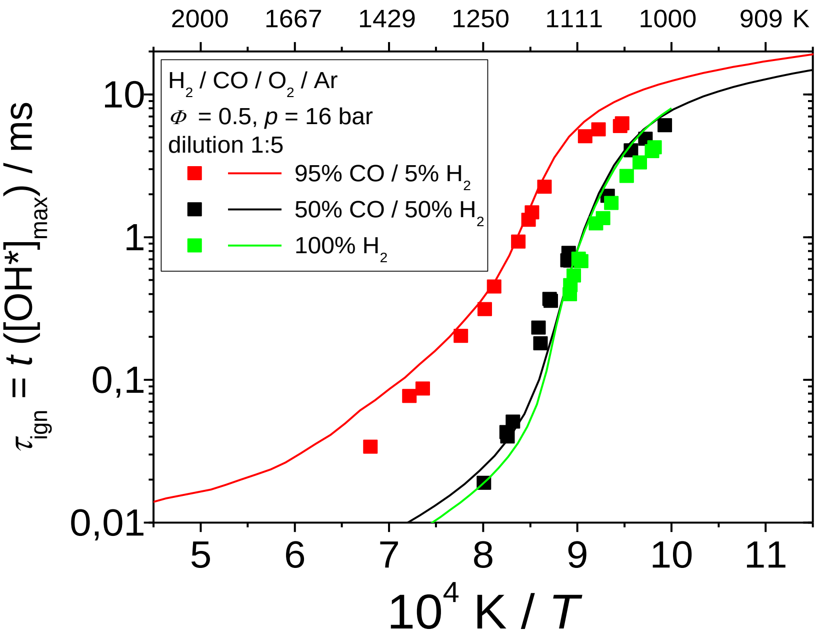


Fig. 1 - Measured and calculated ignition delay times of different H_2 / CO / O_2 / Ar mixtures (Φ = 0.5, dilution 1:5) at 16 bar. Symbols: Experiments. Lines: Simulations considering temperature increases due to gas dynamical effects using the Li et al. 2007 mechanism.

The most important findings can be summarized as follows

- the GRI 3.0 mechanism exhibits apparent deficiencies with experimental data for H2 (rich fuel gases) in terms of ignition delay time, laminar flame speed and NOx emission
- specially developed mechanisms (for H2 rich fuels) show a good prediction performance for ignition delay time and laminar flame speed, but
- some mechanisms lack the additional capability to predict NOx emissions comparably well

Only the reaction mechanism developed within the H2-IGCC project shows good performance in all three combustion parameters (ignition delay, laminar flame speed and NOx emission).

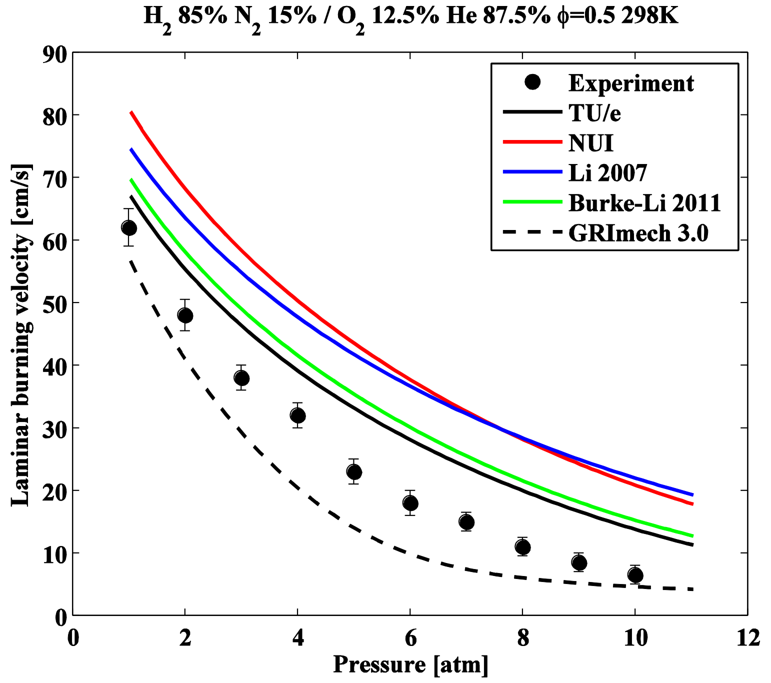


Fig. 2 - Measured and calculated laminar burning velocity for a H_2 / N_2 / O_2 / He mixtures (Φ = 0.5) at different pressure levels (up to 10 bar). Symbols: Experiments. Lines: Simulations based on different reaction mechanisms.

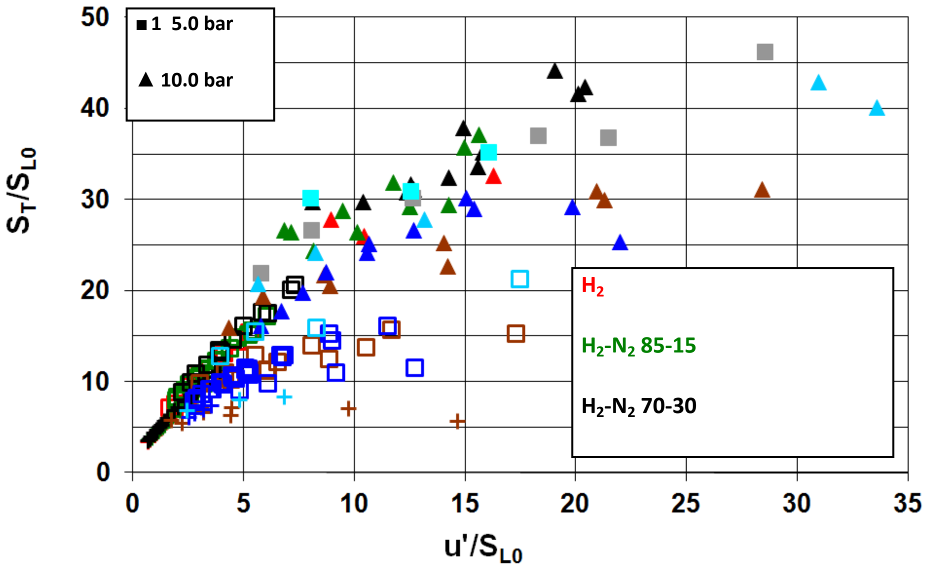


Fig. 3 - Normalized turbulent flame speed data for various H_2 /CO/ N_2 mixtures at different pressure levels (up to 10 bar) in dependence of the normalized turbulent intensity.

All experimental data and operating experience reported for the combustion demonstration activities in the following paragraphs are based on single burner testing with simulated gas turbine operating conditions. The experimental trials were carried out at different test rigs (Combustion Test Facility of University of Genoa at Savona, Italy; High Pressure Optical Test Rig at Cardiff University's Gas Turbine Research Centre, UK; ENEL Research Lab at Sesta, Italy) simulating gas turbine operating conditions from start-up/engine ignition up to full load (scaled for reduced pressure ; e.g. at 3 bar_a, this corresponds to an equivalent thermal power of 2.0 MW at base load condition). In total about 12 different burner configurations (designed and manufactured by Ansaldo Energia, Italy) were evaluated, at a range of conditions from atmospheric pressure up to 13 bar_a.

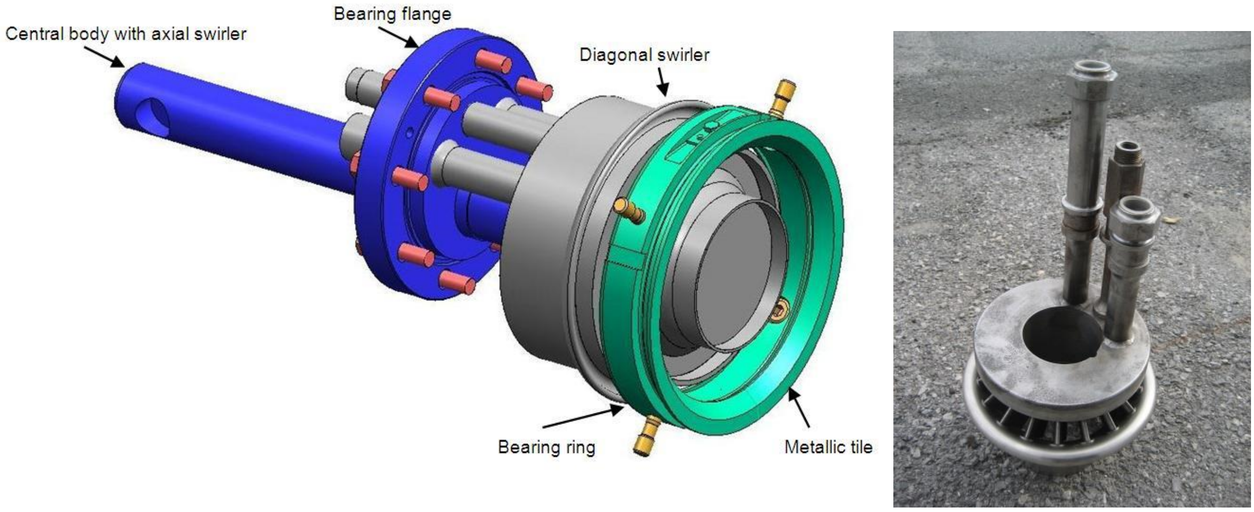


Fig.4 - Schematic burner configuration (left) and scaled prototype burner hardware

The best configuration tested has been the one with a diagonal swirler with standard blades height, larger fuel injection hole diameter, reduced swirl and with the outlet section reduced by 60% (compared to a standard burner design used for natural gas operation). This burner design solution integrates different features which all together work against flashback occurring while operating the burner with H_2-rich fuel mixtures (up to 85%vol. H_2).

In some of the test runs (especially for elevated operating pressure at the ENEL Research Lab at Sesta) the hydrogen concentration in the fuel gas mixture has not been very reliable due to unsteady operation of the on-line mixing system of hydrogen and nitrogen. It has not been possible to keep the fuel gas composition constant during longer periods of rig operation (indicated by gas chromatographic measurements giving evidence of the variation but only with a delay time of about three minutes). This system behaviour has increased the test complexity considerably and has been a limiting factor during all the test campaigns.
For most of the trial runs the syngas composition has been maintained as close as possible to 85%vol. H_2 and 15%vol. N_2, but at operating pressure conditions above 3 bar_a, a lower percentage of hydrogen (50-70%vol.) has been used part of the time (e.g. during pressure transients) as a precaution against flashback, which could still not be completely avoided and has been experienced a few times as a sudden, non-reversible phenomenon.

Test points have been calculated from gas turbine engine operating conditions, scaled for lower pressure.

For ignition/light-off the following procedure has been applied:

1. Flame ignition with methane (standard diffusion pilot)
2. H_2-rich syngas addition (via premix fuel injection system)
3. Methane pilot cut-off
4. H_2-rich syngas operation (premix only; no piloting)

2. Full Load Operating Characteristics

Full thermal load of the burner at full pressure conditions (i.e. – unscaled -Base Load at 15bar) could not be achieved in any of the test campaigns performed. Even though successively higher operating pressure could be covered in a safe and stable combustion mode by introducing certain design modifications to the burner hardware (measures taken see above), each test campaign at a given pressure level indicated certain operating restrictions given by the occurrence of flame flashback (i.e. flame positioning inside the burner hardware close to the fuel injection location).
The most significant points of the tests are the following:

1. Achievement of a Base Load scaled for 3 bar with 70%H_2-30%N_2 syngas composition.
2. Achievement of a Base Load scaled for 5 bar with hydrogen percentage between 70 and 55%. The humming appears cyclically with amplitude of 10-25 mbar and a frequency between 650 and 850 Hz, most likely due to the syngas composition variation. NOx emissions are between 10 and 20 ppm.
3. Achievement of a stable Base Load scaled for 7 bar with 64%H_2-36%N_2 syngas composition. NOx emissions around 6-7 ppm.
4. Achievement of a stable Base Load scaled for 9 bar with hydrogen percentage between 75 and 70%. NOx emissions around 15-16 ppm.

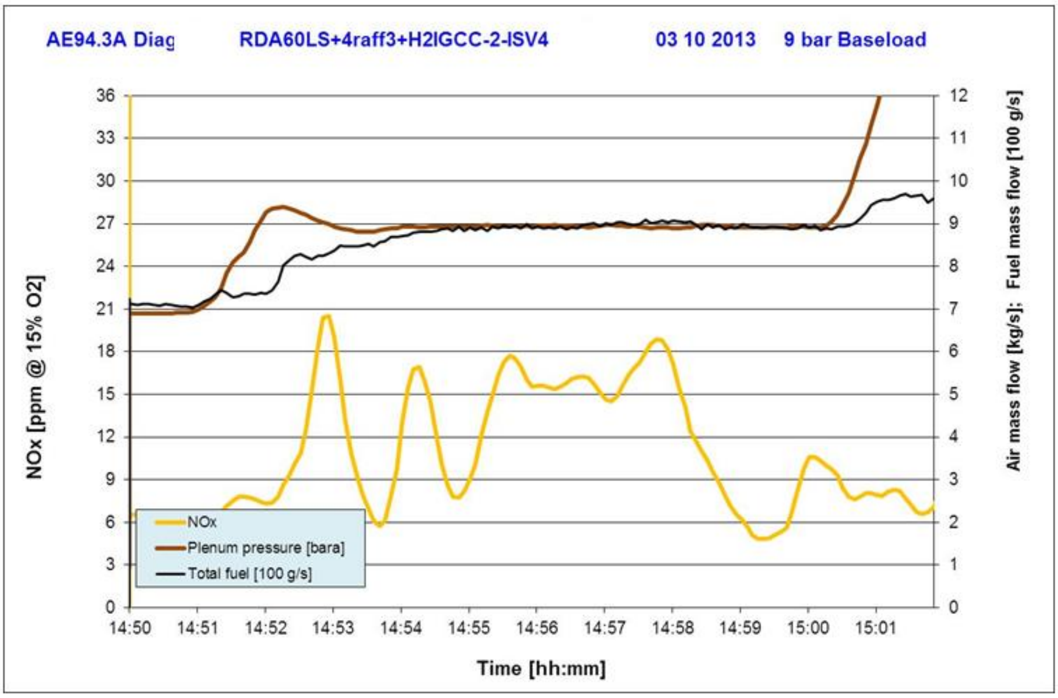


Fig. 5 - successful test run at reduced (9 bar_a) base load condition with NOx emission in the range of 15 ppm @15%O2.

5. Shortly before the achievement of the Base Load scaled for 13 bar with hydrogen percentage probably around 70%, the flashback has occurred. The manual trip has not been fast enough (5 seconds) to save the diagonal swirler. The flame could not be extinguished within a short enough time to prevent overheating of the swirler vanes close to the fuel injection ports (due to the fuel gas volume contained in the pressurized fuel supply system which is unavoidably released into the combustor after the main fuel valve is closed).

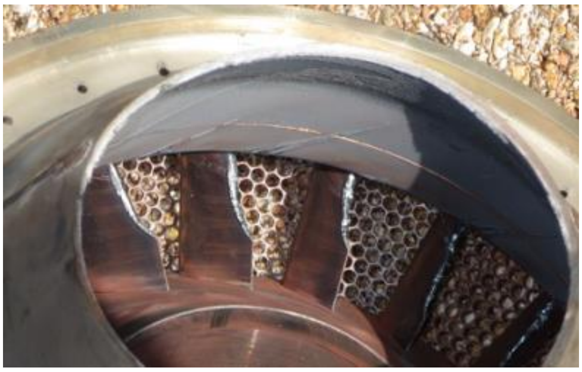


Fig.6 - Diagonal swirler blades after tests

The higher flame temperatures of hydrogen over natural gas for certain fuel/air mixture stoichiometries resulted in a potential for increased NOx emission. But as Fig. 7 shows, the issue is less critical than originally anticipated. For the medium pressure tests, it was clear that improved mixing (via earlier upstream syngas injection) ensured that there are fewer localised fuel rich pockets which resulted in lower NOx formation and more homogeneous heat release. The latter having a positive impact on combustion instabilities as well.
When using one of the more stable design configurations, there was a clear relationship between NO_x and Adiabatic Flame Temperature, exceeding in some cases (Tflame > 1600°C) the nominal 15ppm design threshold. Modifications to the burner design (such as smaller exit area, i.e. increased exit flow velocity) which were taken to expand the operating range (i.e. to prevent flashback), also had effects on the NOx emission. There was a limitation to how far the area of the burner exit (circular burner outlet, CBO) could be reduced, as NO_x emissions increase and the risk of blow off for operation with natural gas increases. If the final burner design must be fuel flexible (operation with H_2-rich fuel gas as well as with natural gas) then design conflicts are apparent at this stage.

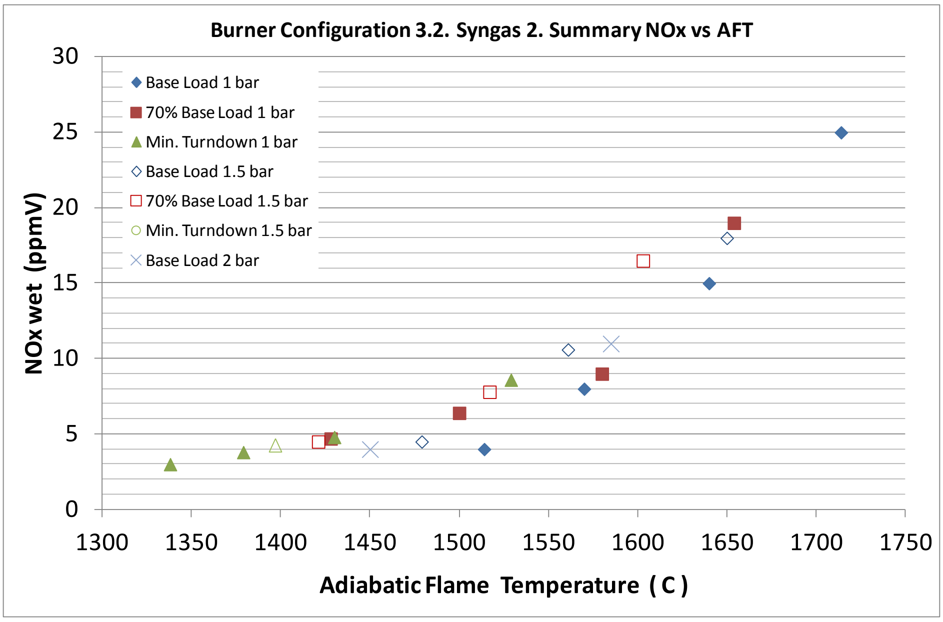


Fig.7 - Typical NOx emissions for H_2-rich fuel mixtures (70-85%vol. H_2)

3. Start-up and Low Load Operating Characteristics

The Flame ignition with natural gas pilot is very difficult with the modified burner configuration because the flame blows off more easily. It is necessary to help the flame with a secondary natural gas pilot and the syngas premix is injected earlier on than with the basic configuration. This behaviour can be explained by the higher velocity at the diagonal swirler outlet (due to the reduced cross-sectional area of the CBO).

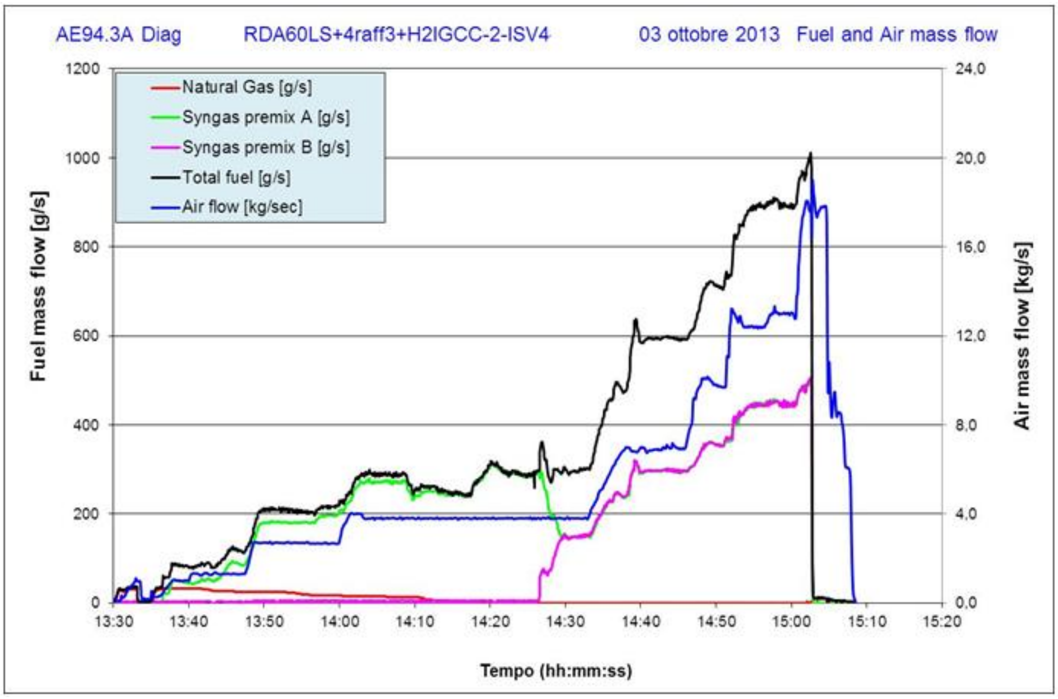


Fig. 8 - Ignition with NG; H_2 enriched syngas was added shortly after; NG support was steadily decreased until a Syngas only flame was obtained.

4. General Conclusions

During the test, several anomalies arose when the control system tried to maintain the fuel gas quality at the requested composition. In a stable condition, when neither the combustion air process parameters neither the fuel mass flow was changing, NOx emission still experienced very wide oscillation, ranging from 1 to 70 ppm. This is evidence that the actual fuel gas quality (H_2 content) was changing rapidly (not picked-up by the gas chromatography measurement due to limited time resolution) and had of course significant impact on the operating characteristics observed. These peculiar operating boundary conditions must be taken into consideration in the analysis of the flashback behaviour, but emphasize on the other hand the high sensitivity of safe/stable burner operation towards varying fuel composition.

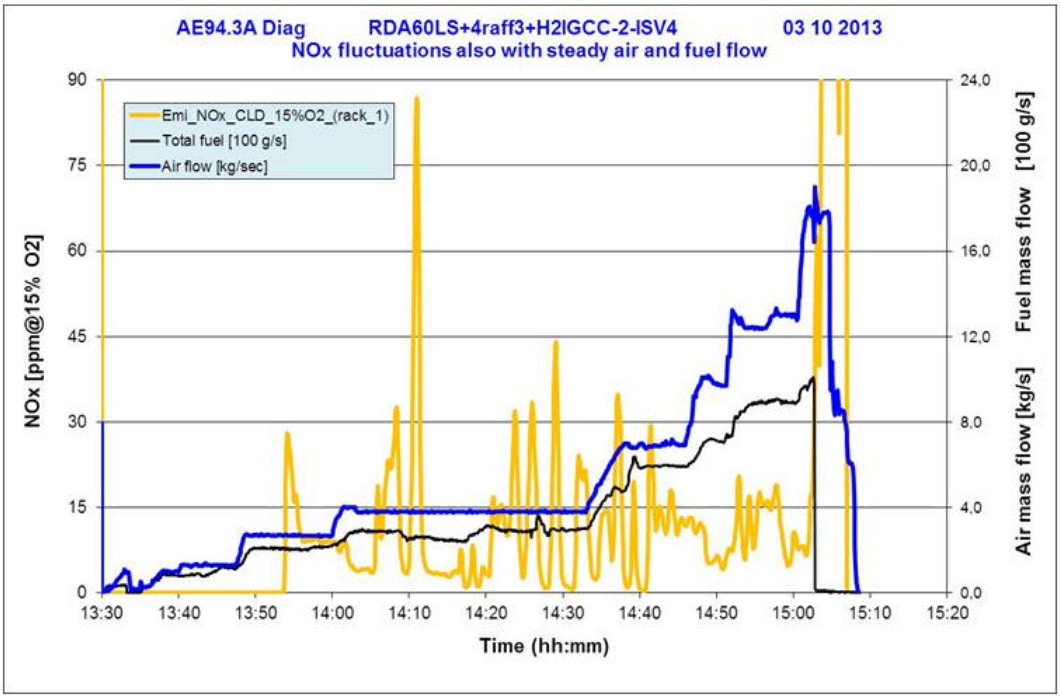


Fig. 9 - High NOx emission fluctuations were experienced (even for constant air and total fuel flow conditions) indicating effects of fuel composition changes (varying H_2 content in the fuel gas mixture).

Increased NOx emission has shown to be an issue less critical than originally anticipated. As improved (fast) mixing of H2-rich fuel gas with the combustion air has shown to improve the operability of the burner (wider operating range without critical pressure pulsations caused by unstable flame positioning), also NOx emission characteristics did benefit from this measure and NOx emision levels could be kept at acceptably low levels (less than 15ppm NOx up to flame temperatures of 1600°C).

Pilot fuel injection of H2-rich syngas (in diffusion flame mode) proved to be detrimental in terms of operating characteristics (pulsations) as well as for the emission performance (high NOx emission) and has been discarded after some initial testing. H2-rich syngas does not require additional flame stabilization via local fuel enrichment (pilot fuel injection) due to its high reactivity, and can maintain stable flame configurations down to ultra-lean operation conditions which occur at start-up/idle and low load operation of the gas turbine.

Although the full pressure has not been reached with none of the burner configurations, useful considerations arose on undiluted, hydrogen enriched syngas combustion in lean premix mode.
Overall it was concluded that the potential for flashback was the largest design challenge when using high hydrogen fuels, which can be overcome to a ceratin extent by increasing the bulk velocity of the reactants through the burner (via reduced CBO area), but this results is a configuration which is hard to stabilise when operating with natural gas. If the final burner design must be fuel flexible (operation with H_2-rich fuel gas as well as with natural gas) then design conflicts are apparent at this stage.

To reach the final burner configuration able to work at the design pressure of the GT further design steps must be considered. A special help could come from CFD calculations based on the flashback model developed in the project. Validation will be carried out using all the experimental tests performed. With the specific reaction mechanism developed in the project, critical parameters ca be calculated for certain flow regions in the burner (especially near-wall regions) in order to realistically estimate the maximum percentage of hydrogen acceptable in the syngas composition, that consents to achieve full operating pressure without the occurrence of flashback.

SP2 - Materials issues

Materials performance is critical to the viability of gas turbines. Over the last 20 years, gas turbine inlet temperatures and component operating temperatures have risen to increase gas turbine efficiency (though the increase in metal temperatures has not been so large due to sophisticated cooling technologies). As a result base alloys have been developed with progressively higher mechanical load capabilities, but at the cost of reduced oxidation and corrosion resistance. To compensate for this a wide range of coating systems have been developed for specific operating environments; initial metallic systems focused on providing corrosion and oxidation resistance (i.e., environmental or corrosion resistant coatings), and then multi-layered ceramic/metallic systems targeted at providing thermal resistance (i.e., thermal barrier coating systems, used in conjunction with blade cooling systems). Thus, the critical components in the hot gas path of a state-of-the-art gas turbines are usually complex materials systems that are the result of many challenging manufacturing processes; typically multi-layered coating systems (with ceramic and/or metallic layers) applied to complex-shaped base alloys (nickel or cobalt based superalloys) manufactured to contain many cooling channels/holes. For the highest metal temperature/stress operations, the base alloys need to be manufactured as single crystals.

The life of components in gas turbines is governed by both the physical and chemical properties of their materials and how these materials interact with the operating conditions, including:

- Temperatures (e.g., bulk metal temperatures, surface temperatures, gas temperatures and heat transfer rates, heating/cooling rates)
- Stress levels (e.g., average stresses, fluctuating stresses, rate of change of stresses)
- Environments around components (e.g., gas compositions, deposit composition, deposition fluxes, particle impact fluxes)

The resulting component lives depend on a balance between these factors, with the most advanced gas turbines trying to use the highest temperatures and stress levels to gain maximum efficiencies. So, the traditional route to introducing a novel gas environment is to use less advanced gas turbine that is not pushing these boundaries (or component materials). An example of this approach within the H2-IGCC project was the ENEL Fusina gas turbine, which used a H2-rich gas mixture as fuel, but also used lower combusted gas temperatures and so permitted the use of blades/vanes that did not required the thermal barrier coatings used in current advanced gas turbine systems.

For this H2-IGCC project, the focus has been to enable the use of state-of-the-art gas turbine operating conditions associated with natural gas fired systems, in a system fired on hydrogen rich syngases. Thus the aims for the materials activities were:

- To understand the dominant materials damage mechanisms in gas turbines burning syngas, hydrogen and natural gas
- To identify and demonstrate state-of-the-art and improved materials systems giving acceptable service lives
- To demonstrate non-destructive evaluation (NDE) methods suitable for monitoring life-limiting damage
- To extend life modelling capabilities to cover the H2-IGCC environments

To enable this to be carried out in a systematic manner, these activities were tackled in a series of six work packages.

WP2.1 Component operating conditions with novel syngases

This WP focused on the assessment of component operating conditions throughout the hot gas paths of the gas turbines fired on syngas and H2-enriched syngas (after CCS), with two key activities:

- To evaluate operating conditions for components in the hot gas paths of gas turbines within advanced IGCC systems (Siemens, Cranfield)
- To identify from ex-service components the damage mechanisms found after exposure in advanced IGCC gas turbine (ENEL, RSE, Laborelec)

Syngas compositions and GT component operating conditions

The approach adopted to the materials activities, based on the use of state of the art component operating temperatures and component designs, meant that the exposure parameters that could influence the life of the components were a result of changes to the exposure environments anticipated around the blades. These environments are a result of the combustion of the fuel gas stream in cleaned combustion air. Three conditions were selected for evaluation:

- Combusted H_2- enriched and fully cleaned syngas
- Combusted partially cleaned syngas (extracted before entry to the water gas shift reactor and CO_2 removal part of the system)
- Combusted natural gas

Combusted natural gas was used as a reference case on the basis that state-of-the-art materials had acceptable performance in the resulting environments around the hot gas path components.

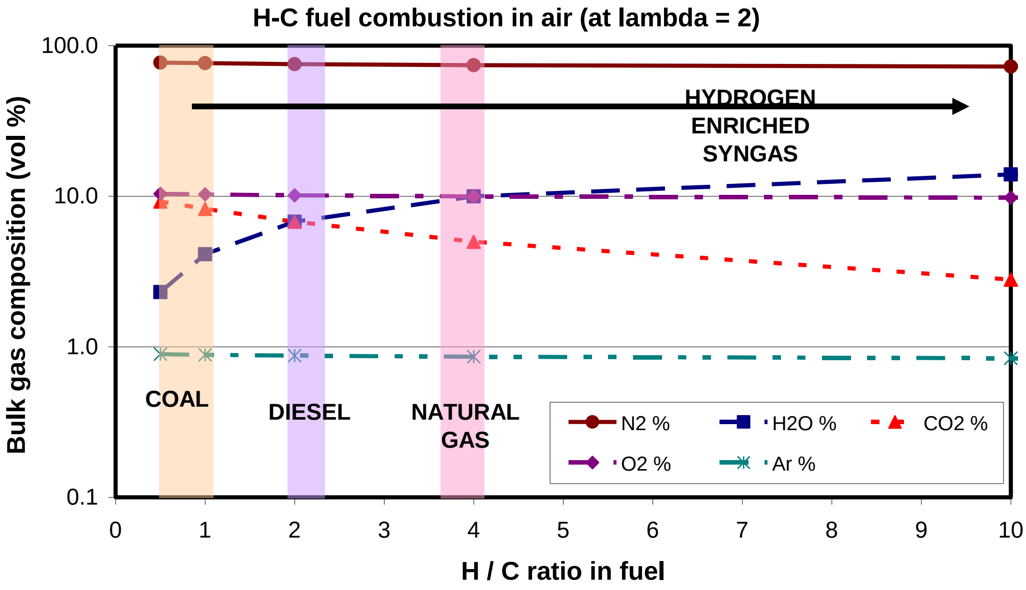


Figure 10 - Sensitivity of combusted bulk gas compositions to fuel atomic H/C ratio

Exposure environment parameters that were considered included:

- Bulk gas compositions (Figure 8):
  - combusted H_2-enriched syngas has a much higher steam content and lower CO_2 content than combusted natural gas
  - combusted partially cleaned syngas has a lower steam content and high CO_2 content than combusted natural gas
- SOx contents
  - Expected to be similar to combusted natural gas for combusted H_2-enriched syngas (due to the additional acid gas cleaning steps required for the use of the water gas shift reactors in processing the fuel gases)
  - Expected to be much higher (at least 20 times) for combusted partially cleaned syngas, as this fuel gas will not have gone through all of the acid gas cleaning steps)
  - Expected to be higher if combustion air filtration system is not optimised
- Alkali metal compounds; Ca, Mg, Al, Si, Fe oxides; and particles
  - Expected to be similar to combusted natural gas for combusted H_2-enriched syngas (due to the extra fuel gas processing steps)
  - Expected to be higher for partially cleaned syngases
  - Expected to be higher if combustion air filtration system is not optimised

High H_2 Gas Turbine Operation and Ex-service components from the ENEL Fusina facility

The operation this gas turbine with blends of hydrogen and natural gas, aimed to evaluate the effect of hydrogen combustion on standard gas turbine materials. The gas turbine was operated for over 2300 hours, before selected components had to be removed for non-destructive and destructive examination (Figure 9). These examinations found only relatively minor damage to the combustion can, transition duct and blades/vanes.

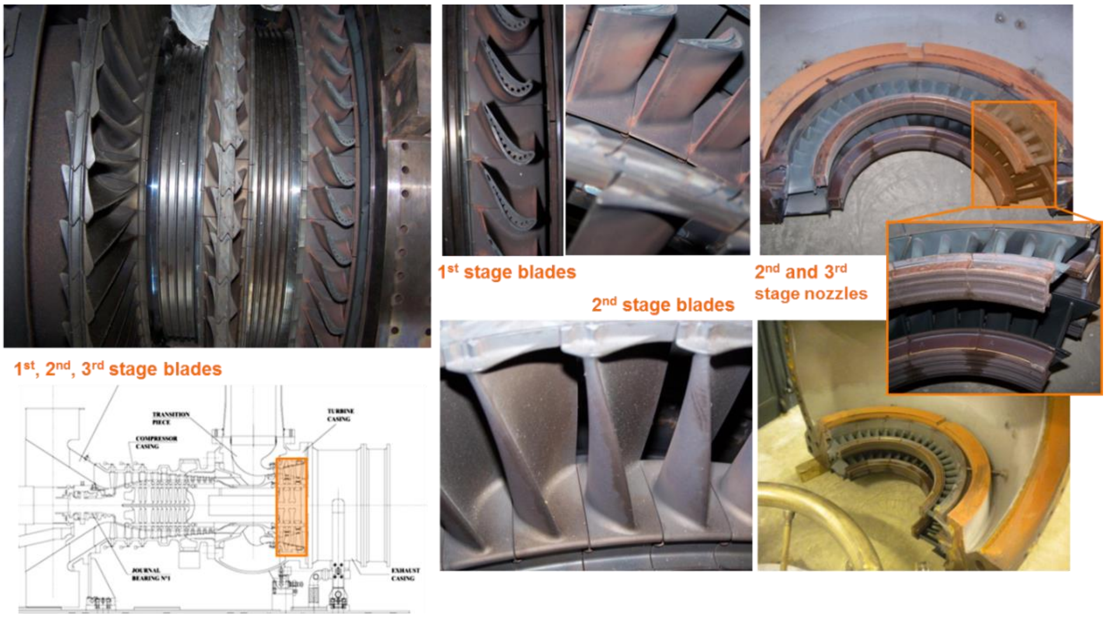


Figure 11 - Photographs of the Fusina gas turbine during inspection

WP2.2 Performance of state-of-the-art materials/coatings in novel operating conditions

A series of laboratory/burner rig test programmes were carried out to evaluate the effects of the various potential changes in exposure conditions identified in WP2.1 to state of the art materials for natural gas fired gas turbines (Table 1):

- Oxidation / thermal cycling – effect of steam content (gases) (FZJ)
- Hot corrosion – effect of SOx / alkali metals / steam (gases and deposits) (Cranfield)
- CMAS corrosion – effect of Ca, Mg, Al, Si, Fe oxides (deposits) (FZJ)
- Erosion – effect particles (RSE)
- Mechanical properties – effect of gas steam content on creep (Laborelec), thermo-mechanical fatigue (RSE), small punch creep (RSE)
- Thermal properties – effect of gas steam content (RSE)

Base Alloys	Metallic coating (bond or corrosion resistant)	Ceramic thermal barrier coating (TBC)
• Rene 80 • GTD111 • PWA 1483 • MarM 509 • Hastelloy X	• SC2464 (MCrAlY applied by high velocity oxy-fuel spraying, HVOF) • SC2231 (MCrAlY applied by HVOF) • RT22 (Pt-Al applied by electro-plating and aluminising)	• Air plasma sprayed (APS) 8% yttria – zirconia

Table 1 - State of the art materials selected for evaluation (note: only selected combinations of base alloy and coatings were investigated)

These exposure programmes generated a large amount of detailed data on materials performance (e.g., Figure 10) which has been used within this project for the development of life prediction models (WP2.5). Many of these data are also being used as the basis for publications in journals and at conferences.

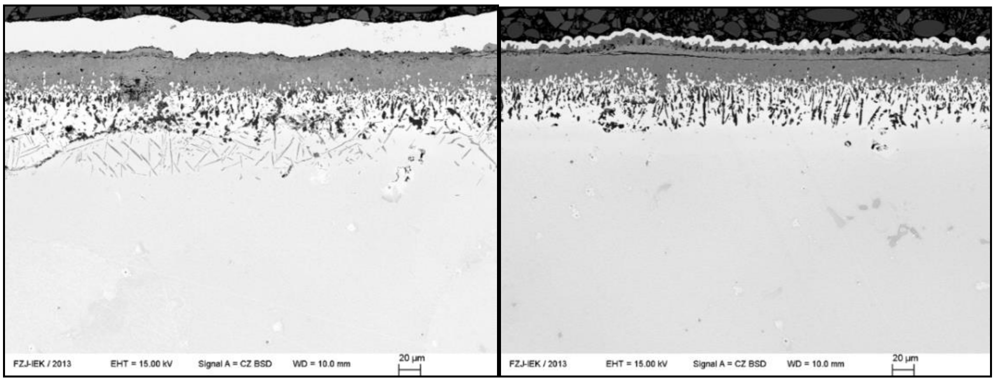


Figure 12 - SEM cross sections of Rene 80 + SC-2464 after exposure at 950°C for 1000 h in synthetic air (left) and synthetic air + 20%H_2O (right)

WP2.3 Advanced NDE and monitoring methods

Activities were targeted at evaluating the effectiveness of advanced NDE / monitoring methods when used on components exposed to novel operating environments. A wide range of potential NDE techniques were considered before work was focused onto three systems that had potential for significant development:

- Flash thermography - to identify and characterise crack propagation in/under advanced thermal barrier coatings (Figure 11)
- Raman spectroscopy – to characterise phase stabilities and stress development in TBCs and thermally grown oxides (TGOs)
- F-Sect analysis – to characterise bond coating thicknesses beneath TBCs

These systems were all used on a wide range of laboratory and ex-turbine samples (from Siemens), to develop improved understanding of their outputs and to enable calibrations to be generated. Then the systems were demonstrated on the components taken from ENEL's Fusina plant (WP2.1) and the blades exposed in Cranfield's burner rig cascade (before and after exposure) (WP2.6).

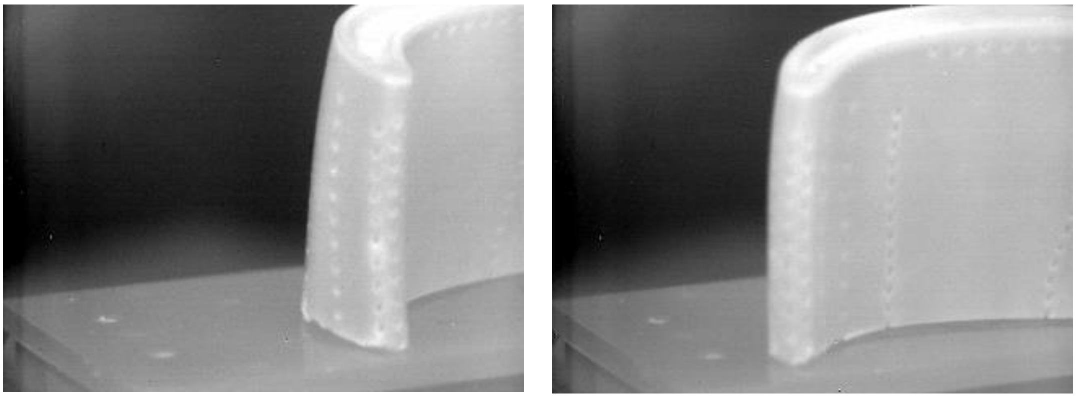


Figure 13 - Thermographic images of an APS TBC coated gas turbine blade (white areas show sub-surface defects)

WP2.4 Identification of improved materials/coating solutions to resist novel environments

This WP focused on identifying potential new TBC and corrosion resistant coating systems to protect components in the most aggressive combusted syngas environments and assessing their performance.

A wide range of potential novel TBC systems were identified. These were down selected through a series of screening trials and by consideration of the reliability of the coating application processes used to create the trial samples. A potential new bond coating composition was identified from the small-scale bulk alloy work into several potential compositions carried out at Sheffield University. Initial oxidation studies were conducted to identify the most promising composition. From the range of proposed solutions four promising novel coating systems were identified:

- 2 new bond coats (FlashCoat, ; rough Air Plasma Sprayed (APS) "Flashcoat" layer on top of the HVOF bond coat to improved TBC adherence, produced at Flame Spray, and one designed at Sheffield)
- 2 new thermal barrier coatings (a double layer thermal barrier coating, including an outer ceramic $Gd_2Zr_2O_7$ layer to resist CMAS attack, produced at FZJ, and a segmented thermal barrier coating, applied by Flame Spray).

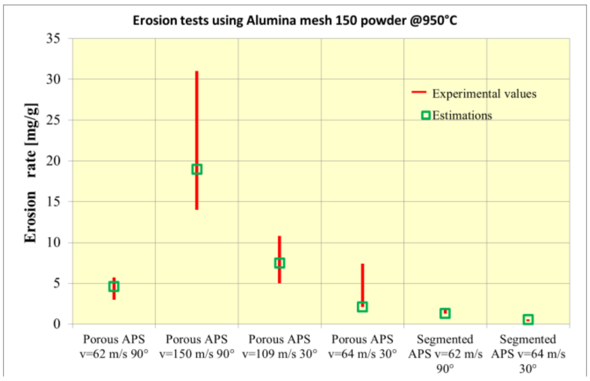
The performance of these were investigated in a series of laboratory thermal cycling/oxidation, CMAS corrosion, hot corrosion and erosion exposures, as well as in burner rig tests and the two most promising systems were applied to blades as part of the cascade demonstration activity (WP2.6).

WP2.5 Life prediction of components using existing materials systems

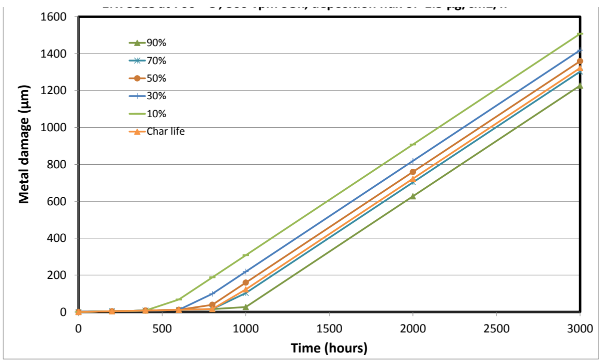
This WP was focused on developing improved models for the prediction of component lives in gas turbines that are part of advanced IGCC systems and validating these improved models. To make best use of the extensive materials performance data generated by within this project, a series of models were developed related to specific degradation mechanisms:

- Erosion (RSE)
- Thermal barrier coating life (RSE)
- Hot corrosion (Cranfield)
- CMAS corrosion (FZJ)

These models were developed using fundamental principles whenever possible (e.g. for the erosion damage) and empirical data from the test programme to support the currently more limited mechanistic understanding that exists for the corrosion related degradation (e.g. Figure 12).



(a) Erosion data compared to modelling predictions



(b) type II hot corrosion model example prediction

Figure 14 - Examples of predictions from erosion and hot corrosion models

WP2.6 Demonstration of new materials/coating solutions in novel operating environments

This WP had three main activities:

- Demonstration of the successful application of advanced coatings to real blades (Siemens, Flame Spray and Julich) – Figure 13
- Exposure of blades with advanced and state of the art coatings in a burner rig cascade (Cranfield and Siemens) – Figure 14

- Demonstration of the advanced NDE techniques (from WP2.3) on the coated blades before and after their exposure (RSE and Laborelec)

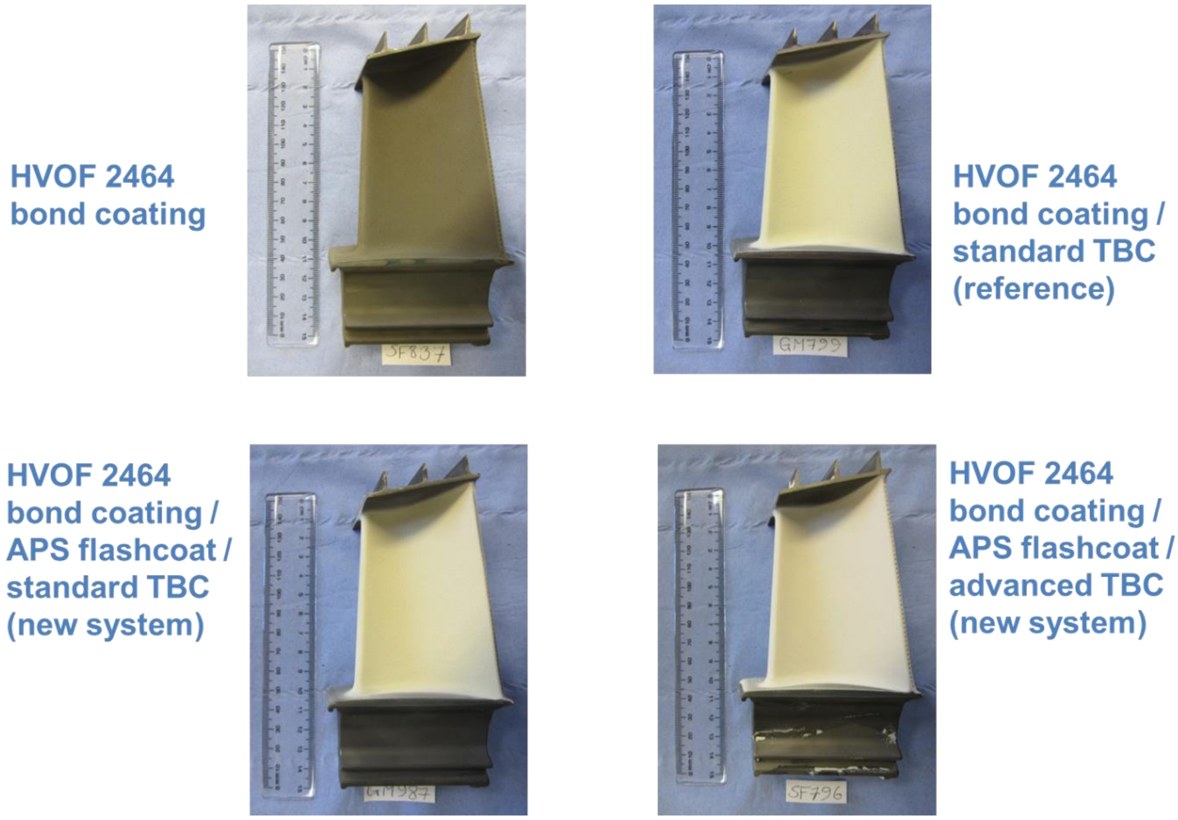
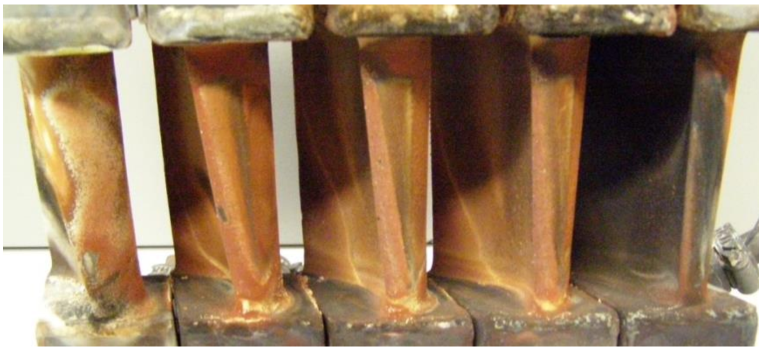


Figure 15 - Examples of coated blades prepared for exposure in the burner rig cascade

(a)



(b)

Figure 16 - First cascade blade cluster after 1000 hours operation: (a) upstream view and (b) downstream view

Summary

From the laboratory tests carried out, there was little difference between the environments generated by combusted natural gas and combusted H2-enriched syngas. The higher steam contents of the combusted H2-enriched syngas caused some microstructural differences in oxidation products during high temperature oxidation, but the effect on TBC spallation was less than the scatter caused by coating manufacturing issues. Also the creep and fatigue lives were similar in the different environments tested. The advanced coating system that included the "flashcoat" layer appeared to offer improved TBC lifetime performance in many tests.

The combusted hydrogen-enriched syngas did not cause significantly more damage than combusted natural gas in demonstrations in either ENEL's Fusina gas turbine or Cranfield University's burner rig cascade trial.

The combusted partially cleaned syngas environments caused significantly (10 times or more) more damage than combusted natural gas in all the relevant test programmes (hot corrosion, CMAS/F corrosion and erosion). Thus, the use of partially syngas needs to be treated with caution. One particular concern is that once contaminants have entered the various fuel gas ducts and the gas turbine hot gas paths, they may prove to be difficult to remove and so lead to on-going damage at a higher level than expected from the fully processed gas. Under some conditions the additional outer ceramic of $Gd_2Zr_2O_7$ was successful in resisting CMAS attack, but it had increased spallation under thermal cycling conditions, indicating that the coating microstructure/manufacturing route needed to be optimised further.

SP3 - Turbomachinery

It was recognised from the outset that firing hydrogen rich Syngas in a gas turbine that is originally designed for Natural gas combustion brings about a number of significant technical challenges to the compressor, expander and expander cooling system. Thus this subproject had the task of evaluating the extent of these problems and proposing design solutions that are economically viable by minimising design changes to the turbomachinery components and minimising impact on the power plant. The issues that have been addressed are:

- The substantial variation of the turbine inlet volumetric flow rate, due to the increased amount of fuel (and fuel diluent), would significantly affect the original matching of the expander with the compressor. Considering the common turbine chocking condition for heavy duty industrial power plants, the larger fuel flow rate would lead to a lower demand of air from the compressor and, more in general, increase of compressor back-pressure reduce or diminish the surge margin.
- The higher turbine inlet volumetric flow and different exhaust gas properties will influence the aerodynamic performance of the turbine. In addition, a reduction of the cooling effectiveness is expected due to the higher mass flow rate and higher specific heat of the combustion exhaust combustion products that have higher water vapour content.
- A change in the circumferential temperature distribution at the combustor outlet might give rise to low engine order excitation of the downstream turbine stages due to the potentially different propagation pattern of hot streaks within the expander

In summary, the issues encountered are compressor instability due to the mismatch between the compressor and expander, expander performance, cooling and integrity.

This SP had four partner institutions with complimentary expertise necessary to conduct the tasks effectively. The subproject partners and their expertise are:

- University of Susses, which was subsequently replaced by City University London due to the move of the principal investigator, have expertise in compressor three-dimensional design and analysis using CFD tools and expertise in expander aeroelasticity and low engine order analysis.
- RWTH Aachen University with expertise in expander design and CFD analysis.
- CENAERO with expertise in detailed cooling flow geometries and conjugate CFD and heat transfer analysis.
- University of Roma Tre with expertise in turbomachinery one-dimensional design and optimisation, component matching, control and cooling.

To conduct the subproject tasks and propose practical solutions to the above mentioned problems, it was essential to acquire gas turbine compressor and expander geometries that are representative of modern industrial gas turbines of the 300 MW class that was agreed to be the vehicle for developments in this project. Gas turbine geometries are typically confidential and are not available in the public domain in a level of detail sufficient to conduct the required analyses. Thus it was decided from the outset to design a generic geometry representative of modern gas turbines of the identified class that can be used as a vehicle for the investigations and proposed solutions. One major advantage of using such geometry is the ability to disseminate the results widely without confidentiality restrictions.

The generic geometry

It was decided to design Natural Gas fired gas turbine geometry as a reference or a baseline for design modifications. A procedure similar to that used by OEMs was followed in the design process. The procedure can be summarised in the following steps.

- The basic design of the gas turbine was established using a power plant simulator that uses specifications from a database that contains information from a wide range of modern gas turbines in operation. The simulator relies on some specified geometric and flow and heat transfer parameters constrains and uses an iterative and optimisation approach to specify the necessary data for the gas turbine design. These primarily specify data such as number of stages in the compressor and expander, pressure ratios for each stage, velocity triangles, nominal blade profiles and other details required to create the three dimensional geometry. The Siemens SGT5-4000F and the Ansaldo AE94.3A have been selected as the main reference gas turbines for providing data to design the generic geometry. The geometry outline created is shown in Fig 1.

- The three-dimensional compressor geometry was created using the above step as a starting point. Blade profiles were designed stage by stage. CFD analyses were used to investigate the design allowing for fine turning to match the constrained parameters. All stages were subsequently put together into a set of whole compressor CFD calculations that allowed for further fine-tuning of the design ensure stage matching. A complete compressor characteristic map was then produced using CFD, which showed good agreement with that predicted using the one-dimensional model that is typical of modern gas turbine compressors. A view of the compressor geometry is shown in Fig 2 together with the compressor characteristics map.
- A similar approach was followed to create the three dimensional geometry of the expander. The resulting blade profiles were then used as a starting point for designing the detailed internal blade cooling geometries. A view of the turbine geometry is shown in Fig 3.
- The internal blade cooling geometries were produced using details from similar gas turbines. Scaling and other modifications were used to ensure matching between the blade profiles and the internal cooling geometry. CFD and conjugate heat transfer analyses were conducted including flow outside and within turbine blades to ensure the blade surface temperatures marched those specified by the one-dimensional model. A view of the internal cooling system is shown in Fig 4.

The resulting generic gas turbine geometry was used as a starting point for modifications required to accommodate Hydrogen-rich syngas operation. Producing a gas turbine generic geometry is a significant achievement in this subproject. This geometry is available for use with other similar projects.

Modifications for syngas operation

In order to solve the compressor/turbine mismatch several options have been discussed and explored. This activity was coordinated with SP4. The proposed modifications can be summarised as follows:

- Reduce the firing temperature and/or blow off the amount of the air that cannot be sent through the gas turbine.
- Accommodate the higher combustion exhaust flow rate by raising the swallowing capacity of the expander.

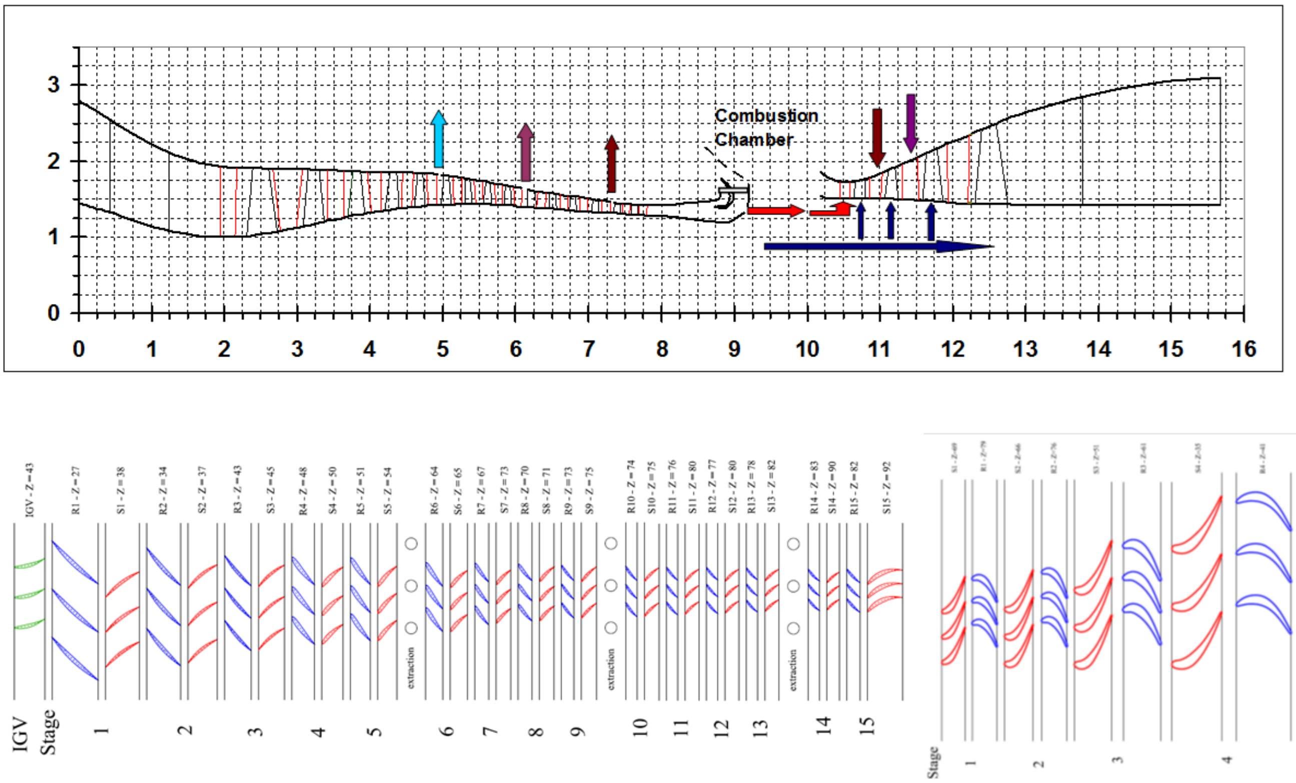


Figure 27 - Reference gas turbine geometry

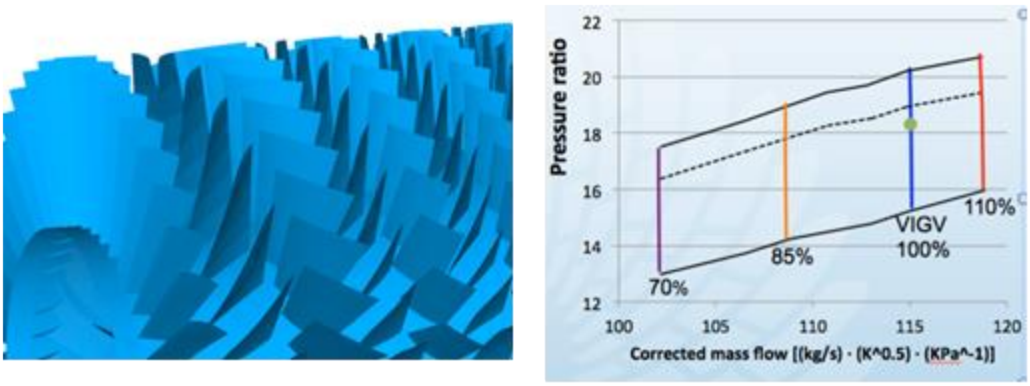


Figure 38 - Compressor geometry and characteristic map

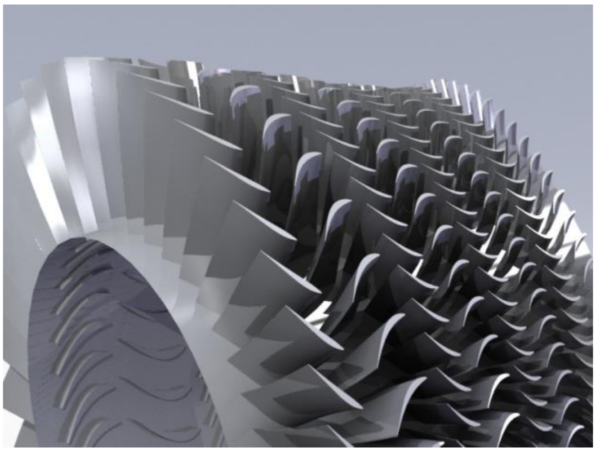


Figure 49 - Expander geometry

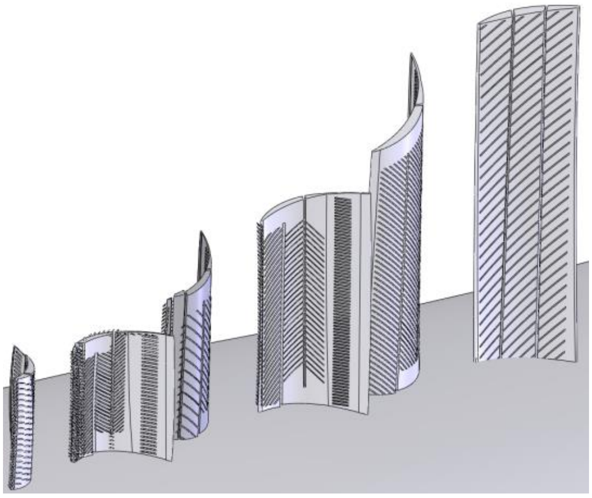


Figure 20 - Expander internal cooling

- Allow for an increase in cycle pressure ratio by adding one or more compressor stages.
- Combine some (or all) of previous solutions.

The criteria for the final chosen solution was based on minimising modifications to the system while, at least, maintaining the original machine's performance levels.

The first solution of reducing the firing temperature and/or blowing off the excess air was analysed using the one dimensional gas turbine simulator. It showed that reduction in the firing temperature leads to reduction in power output of the gas turbine, which is undesirable. The viability of blowing off the excess air as a solution depends on the degree of integration of the gas turbine with the air separation unit and gasifier. Current experience shows that full integration could cause problems and thus this solution is not recommended.

It was found out that in terms of combined cycle performance the best solution is represented by the expander geometry modification when a reduced LHV Syngas fuel is burned in the machine. On the other hand, the reduction of the compressor air supply also represents a very interesting option due to the possibility of minimising the need of major cooling system and bottoming cycle modifications. This is due to the fact that, differently from the other options, such solution would not significantly change the TIT, pressure ratio and turbine inlet flow rate of an existing machine. Therefore, both these solutions were considered and analysed in detail. Based on the mean line calculation and re-sizing of the machine, the gas turbine components have been re-designed and their behaviour investigated by means CFD analyses.

Reducing the compressor airflow by means of modulating the variable inlet guide vane (IGV) was deemed insufficient. The analysis showed that safe operation could only be ensured for about 5.5% reduction in mass flow using this approach. However, compressor flow reduction for conventional combined cycles is typically within 10-15% when the IGV is the only variable vane and thus this solution was deemed insufficient. The Siemens SGT5-4000F compressor, on which the baseline compressor design is based, is provided with a VIGV, while Siemens class H machine (SGT5-8000H and SGT6-8000H) are also equipped with 4 variable stator vanes, VSVs. Thus, using one dimensional analysis, the stagger angle of the first four stator blade-rows have been left free to move at the new nominal compressor inlet mass flow rate, while the IGV was kept at its original position. 3D CFD analyses were used to verify this approach and fine-tune the VSV angles. The analyses showed that the original pressure ratio and surge margin were re-established. Moreover, the results indicate that the new configuration would allow for stable and safe part-load operation up to IGV 70% closing, corresponding to an airflow modulation of about 11.5%.

Adding a stage to the compressor to allow operation at a higher-pressure ratio was deemed unsuitable because it leads to deterioration in compressor performance and also the requirement that the turbine operates at higher pressure, which also affects cooling flow arrangements.

It was concluded that compressor modifications require significant changes to the machine and the resulting changes in operating conditions will affect the bottoming cycle. The changes to the expander were favoured as they minimise geometric changes to the gas turbine and engine operating conditions.

Thus to maintain the nominal pressure ratio without modifying the compressor when the gas turbine is fed by 33MJ/kg Syngas, the 1st Nozzle Row (NGV) opening needs to be increased. This was achieved by changing the stagger angle of the NGV. Re-staggering of the NGV allows the expander to accommodate a higher gas mass flow rate and maintains the pressure ratio at the reference value thus no modifications to the compressor are required.

Re-staggering the NGV by -0.63°, Fig 5, which corresponds to an opening of this blade row, meets the syngas operating point. The throat is increased and, thus, the capacity of the expander is raised. The expander modification was first conducted using the one-dimensional model. Subsequently, three-dimensional CFD analyses were performed to determine the exact re-stagger angle and study effects of this modification on the expander performance. It was found that the expander efficiency experiences a decline of about 0.2% compared to baseline operation. Due to the lower stator 1 exit flow angle there is less work extraction in the first stage. The last stage, on the other hand, experiences an increase, which explains this small reduction in the expander efficiency.

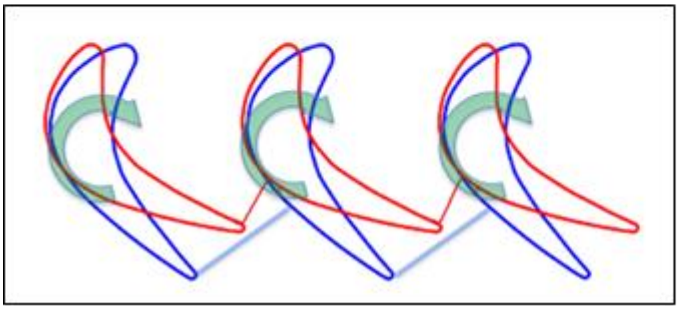
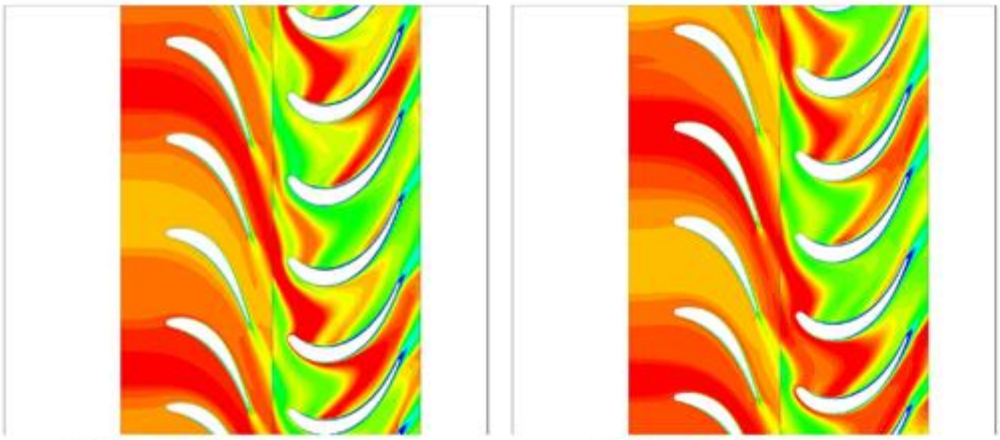


Figure 25 - Re-stagger of the expander NGV

Detailed cooling flow and conjugate heat transfer analyses were performed on the expander to ensure that the cooling flows are sufficient to keep blade surface temperatures at least at their NG operation values to maintain life of the expander components. The analyses show that small increases in cooling flow rates are required to achieve this target.

The final task in SP3 was to investigate whether the changes in the properties of the exhaust gases would lead to significant changes of hot streak propagation patterns at the exit of the expander. It is known that the temperature distributions at the exit of the expander having circumferential and radial variations producing what is known as hot streaks. Hot streaks typically persist within the expander causing hot spots on the vanes. Additionally, their random variation from one host streak to another could give rise to periodic excitations that are at frequencies lower than blade passing harmonics. Such excitations are not possible to account for at the design stage and thus an investigation was necessary to ensure the modified engine integrity. Three-dimensional aeroelasticity analyses were performed by coupling a structural model of the first rotor to a whole annulus CFD mode. Fig 6 shows a view of the hot streak propagation in the first stage. The baseline and syngas machines were compared. It was found that hot streaks have different propagation patterns in the syngas machine. However, the differences were too small to cause any significant increase in turbine blade vibrations.



(a) Hot streak aligned to stator passage

(b) Hot streak aligned to stator LE

Figure 22 - Hot streak propagation patterns

SP4 - System analysis

Introduction

The project H2-IGCC was organized in four subprojects, due to the wide scope of research topics that needed to be addressed and the large number of partners in the consortium. Given the fact that sub-project four (SP4), Systems Analysis, covers the whole H2-IGCC plant, it was logical to use this work package to facilitate information exchange between all four sub-projects and ensure them using identical boundary conditions. To establish effective and secure data and information exchange between the SPs, a platform was created and maintained by SP4 based on "the master table". This table contains all updated technical project data, with especial focus on data crossing interfaces of the SP-boundaries, i.e. all data generated in one SP and used by other SPs. Besides the master table, SP4 was also responsible for cross SP-coordination activity to ensure sufficient communication and alignment between the SPs. An action list was generated and continuously updated during regular phone conferences (every one and a half month) and the half-yearly meetings to ensure project development according to the project time plan.

Sub-project four's technical boundaries of the power plant were defined by the coal feed into the gasifier and air inlets to the air separation unit as well as the gas turbine, the fuel feed to the gas turbine, compressed CO_2 to the pipeline, electricity interface at generator exit, flue gas from the chimney and the cooling water. SP4 targeted optimal layout and integration of the H2-IGCC plant and its components in terms of technical as well as economic aspects.

The main research tasks of SP4 were carried out by the universities involved, i.e. University of Stavanger (UiS) and Roma Tre University (RO3), in close collaboration with the industrial partners Vattenfall and E.ON UK, who contributed by their inputs based on experience from installations and long-time operation of similar power plants. In addition, Vattenfall provided a validated gasification model that was used for system studies and contributed to the modelling of the plant's transient behaviour and main control loops. Both Vattenfall and E.ON UK, contributed to selection of methodology and development of the techno-economy tool used in SP4. This close cooperation between industry and academia resulted in the development of a practical layout and technological baseline of the H2-IGCC plant which represents state-of-the-art technology and a desired level of integration that covers the needs of the operators to achieve higher reliability and plant flexibility. Nevertheless, the H2-IGCC plant's configuration assumes further improvement of certain components and/or ideally optimized plant's components (e.g. air separation unit).

In addition to the basic optimisation of the process, SP4 was also considering part load cases and transient operation of the plant. On request of the industrial partners, cases in which CO_2 capture and transport system was bypassed due to unavailability of subsystems or low CO_2 taxes, were also investigated.

WP 4.1: Thermodynamic design

The work package 4.1, thermodynamic design, focusing on optimum system integration was performed using the commercial simulation tools Enssim, Aspen Plus and IPSEpro benefitting from the strengths of each of these simulation tools.

The coal input was considered to be a mixture of various trade coals available on the world market. The air separation unit (ASU) was considered to be a stand-alone unit, generating oxygen at a purity of 95 mol%. The selection of the non-integrated ASU (with gas turbine) was motivated by the input from industrial partners and experiences of reduced plant availability from partial or full air-side integration between the ASU and the gas turbine. The number of intercooling stages as well as component efficiency was selected according to the "state of the art" technology. The low-pressure nitrogen produced at the ASU is vented to the atmosphere, as the gas turbine is operated with undiluted hydrogen-rich syngas.

The gasification technology was selected to be an entrained flow, oxygen-blown, dry-fed gasifier based on Shell Coal Gasification Process (SCGP). The selection of such a technology was justified due to its high cold gas efficiency, availability of a validated model within the SP4, and its proper operating pressure required for delivery of the syngas at desired pressure to the fuel valves of the gas turbine combustor. Utilisation of the heat available in the gasification block as well as provision of steam to the gasifier, results in many interaction points between the gasification block and the heat recovery steam generator (HRSG).

The raw syngas, after syngas cooling and scrubbing, is converted to mainly CO_2 and H_2 in a catalytic sour water-gas shift reaction carried out in two reactors in series. This exothermic reaction provided an opportunity to generate saturated steam to compensate for a part of the steam needed for the reaction. This unit is followed by a double-stage acid gas removal unit using the Selexol process. Within the first stage, H_2S and COS (which was converted to H_2S in the shift reaction) are removed, which was generated in the gasification unit due to the sulphur content of the coal. The second stage is to remove CO_2 by decreasing the pressure. The CO_2 capture rate has been set to be 90% considering both economic and technical reasons. The separated CO_2 is entering an inter-cooled compression unit followed by a pump to increase the pressure of the CO_2 stream up to 150 bar. A dehydration unit was also considered to extract most of water content to avoid the risk for corrosion in the transport units.

The gas turbine model was regularly iterated between SP4 and SP3 in order to ensure the use of similar characteristics and identical boundary conditions at the interfaces of the individually optimized gas turbine components

A triple pressure level heat recovery steam generator and the steam cycle downstream of the gas turbine was considered and modelled in connection with the abovementioned plant's sub-systems for further utilization of flue gas heat.

In the course of the project, the overall process went through several iterations and optimization cycles to implement information updates from other SPs as well as considering new and updated operational aspects based on input from the industrial partners. Aspects considered were the impact of changes in the system (layout and operational parameters) on the gas turbine and the selection of the combustor type on the process in terms of influences on the pressure of the gasifier. The evaluation was performed for design as well as for off-design conditions in terms of steady state operation, while transient operation was covered by activities in WP 4.2. Besides using already existing models for some of the plant components, additional models were also developed and linked to the simulation software to close the gaps identified in the beginning of the project. The newly developed models were based on information of already existing similar components and validated against their measured operational data. Therefore, it was possible to ensure reliable and realistic results which are of interest to the industry rather than of purely academically interest.

The main results from the system analysis show that the overall efficiency of the selected IGCC plant with CO_2 capture reaches 35.7% and the unit that requires the largest auxiliary power is the cryogenic ASU, consuming about 10% of the gross power output.

WP 4.2: Engineering design

The sizing of a generic 300 MW F class gas turbine (GT) fed by natural gas (NG), similar to the SGT5-4000F and AE 94.3A of two European manufacturers, i.e. Siemens and Ansaldo Energia, respectively, was carried out in this work package. The analysis of the generic gas turbine modification options to safely operate with

the H2-rich syngas (with LHV of 33.4 MJ/kg) has been also performed. Such options concern compressor flow function modifications of the first stages, addition of one more compressor rear stage, re-staggering of the expander first stage nozzle, and the change of the firing temperature and the compressor blow-off.
Nevertheless, the re-staggering of the first nozzle vane cascade of the expander and the modification of the cooling flows has been adopted to have a gas turbine that can be safely operated by the H2-rich syngas. The detailed high fidelity gas turbine simulators for the original NG fuelled GT and for the one adapted for the H2-rich syngas by first stage nozzle re-staggering have been established. Such simulators enable GT analysis at various loads under changed boundary conditions and the control policies to be established. The GT control policies have been established according to the life consumption rates of the hot components when the GT operates at part load and under changed boundary conditions. The safe behaviour domain has been defined. In addition to the GT components, the exhaust heat recovery steam generator has been selected with three pressure levels. It has been sized and also its simulator has been established. Steam turbine, condenser and pump models have been established to set up the steam bottoming cycle simulator. Accordingly, the simulator of the entire power block has been developed and the conversion efficiency of chemical energy of the syngas into work has been evaluated under various boundary conditions. The power block behaviour maps have been calculated and used for optimization purposes. The whole plant optimisation has been performed and the best layout has been established. To perform such a task, the plant has been subdivided into relevant sections that have been analysed in order to identify interventions expected to improve the annual return rate. The most suitable solutions related to an enhanced heat recovery from the ASU main air compressor and from the CO2 compressor have been evaluated. Heat recovery led to net power production increase and coal savings attainable by substituting the use of clean shifted syngas available heat for coal drying have been investigated. Results show that it is better to perform heat recoveries to increase power production in the steam section. Coal saving becomes attractive only for really high coal prices and low electricity selling prices. The optimum performance is achieved by carrying out heat recoveries both from the ASU after-cooled axial compressor and from the CO2 compressor. The full heat recovery leads to a maximum plant net power augmentation of some 9.7 MW, corresponding to an annual return rate gain of 4.9% in respect to the reference plant.

The dynamic behaviour of the whole plant has been investigated, taking the pressure and the related quantities’ variations into consideration, as consequence of power load changes.

Dynamic plant model has been built as a net of well stirred volumes and resistive elements connected by material streams. Flows entering and exiting each volume change as consequence of pressure variations. The model is focused on description of phenomena occurring inside the plant that have significant contribution to the electric power production. Models of plant sub-sections i.e, CMD, Gasifier, ASU, WGS, AGR and power-island, are connected to build the overall plant simulator. Heat transfer devices are also modelled as second order systems with a time lag depending on fluid velocities and thermal inertia. The oxygen valve opening is related to the pulverized coal flow injected into the gasifier with no time delay.

Differences in time constants of the gasification island and the power island result in relatively slow plant load following. The load change rate is mainly conditioned by the ramping rate of the coal feed system (pneumatic transport) and by the ASU. Improvements can be achieved by storing liquid oxygen during load reduction periods and by using it when the power production has to be increased. Pressure and temperature trends have been studied by varying the storage volumes of main plant equipment.

WP 4.3: Economic evaluation

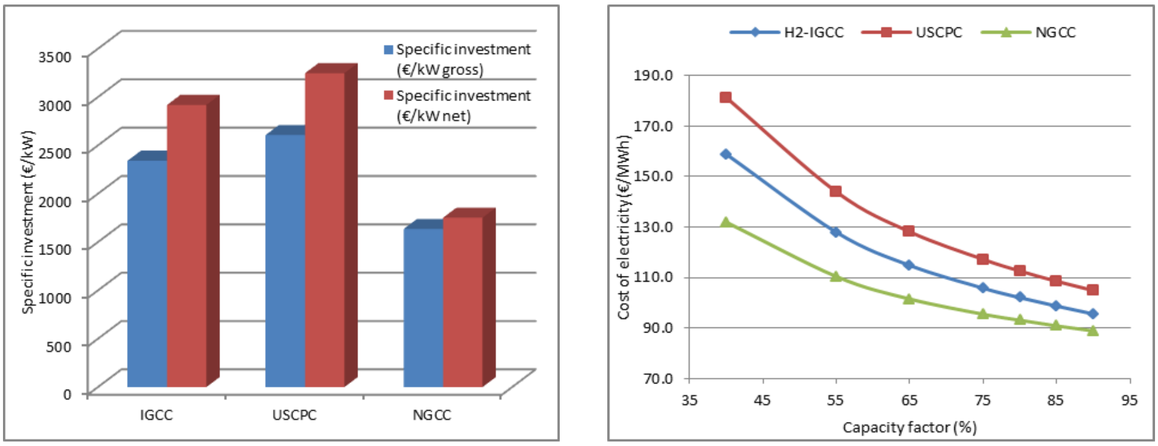
Widespread utilization of any new power generation technology heavily depends on its economic viability as well as its technical benefits relative to other competing technologies. Therefore a techno-economic comparative study was performed to highlight advantages/disadvantages of the selected IGCC plant compared to other potential power generation cycles with integrated CCS. Here the H2-IGCC process was evaluated relative to an ultra-supercritical pulverized coal plant (USCPC) and a natural gas combined cycle (NGCC). Techno-economic assessments have been performed to determine the competitiveness and differentiate between major competing technologies by means of plant's performance and cost of electricity defined by capital investment and production cost.

During the course of the H_2-IGCC project, intensive effort has been put to implement a cost estimation method using more realistic cost data in order to reflect the European power market conditions. In addition, considerable time has been dedicated to internal discussions with industrial partners for selection of the appropriate economic assumptions. Nevertheless, it should be clearly underlined that the cost estimation performed includes a level of uncertainty (+/- 30%) given the fact that there is not any IGCC power plant with CO_2 capture unit in operation. A report, "European best practice guidelines for assessment of CO_2 capture technologies" under European Benchmarking Task Force (EBTF) from EU (FP7) CASEAR project was selected for as a reference for cost data. A model was developed using Microsoft Excel which enables future modifications/changes and implementation of industrial partners' feedbacks. The technical and economic performance of the selected IGCC with CO_2 capture unit, and a comparison with other alternative power generation technologies, the USCPC (300bar/600ºC/620ºC) and the NGCC (based on Siemens SGT5-4000F) were the main outcomes of this work package. The main technical and economic results are shown in the Table 1. The breakdown of the total plant costs for various power plants are illustrated in Figure 1 (a).

In order to evaluate the sensitivity of the cost of electricity for each plant to variations in the capacity factor, a sensitivity analysis was performed. The range of capacity factor was 40-90% and the results are shown in Figure 1 (b). It is evident from this figure that the NGCC plant is less sensitive to changes of capacity factor compared to other plants.

Parameter	Unit	H2-IGCC	USCPC	NGCC
Gross plant's power output	MW	501.4	684.2	385.8
Net plant's power output	MW	402.2	549.2	359.9
Overall efficiency	%LHV	35.7	33.4	48.5
Fuel flow	kg/s	44.8	65.8	14.9
LHV of the fuel	MJ/kg	25.1	25.2	49.7
Total COE	€/MWh	102	109	91

Table 2 - Thermodynamic performance indicators and breakdown cost of electricity for the IGCC, USCPC, and NGCC plants with CO2 capture



(a) (b)

Figure 23 - (a) The breakdown of the total plant costs for various power plants and (b) sensitivity of the cost of electricity to variations in the plant capacity factor

It should be highlighted that techno-economic analysis cannot provide an absolute result, since the cost figures and assumptions on e.g. capacity factor, etc. are uncertain by nature. These factors are market dependent and can change a lot as function of time and geographic location. Based on the level of uncertainty for the economic results of this study (+/-30%), it cannot be concluded that e.g. H2-IGCC is better and more cost effective than the USCPC. Other main derives such as proven technology and operational flexibility will, therefore, play an important role for widespread utilization of these technologies.

Final remarks and conclusions

- System design in collaboration with industrial partners to assure realistic setups, performance indicators, and alternative operational routes
- Gap analysis concerning availability of needed component models and level of detail needed for system studies, followed by complementary model development
- Optimized system integration and performance analysis applied to the base case design and the selected final system layout, including various operational scenarios
- Methodology selection and tool development for techno-economic analysis, using industrial partners' input data for realistic cost/benefit analysis
- Development of control rules and dynamic models for analysis of plant response time
- The optimised H2-IGCC plant with CO2 capture has an electrical efficiency of 35.7% based on the lower heating value (LHV); the main subsystems dominating the plant response time in dynamic mode are coal feeding system and ASU, Differences in time constants of the gasification island and the power island result in relatively slow plant load following. The load change rate is mainly conditioned by the ramping rate of the coal feed system (pneumatic transport) and by the ASU. Improvements can be achieved by storing liquid oxygen during load reduction periods and by using it when the power production has to be increased. Pressure and temperature trends have been studied by varying the storage volumes of main plant equipment. Finally the cost of electricity for the optimized plant layout is 102 Euro/MWh, which can be compared to 109 and 91 Euro/MWh for USCPC and NGCC respectively.

1.4. Potential Impact

The results of H2-IGCC project have matched the EC 2008 Energy Work Programme enabling application of novel gas turbines in large scale IGCC plants with carbon capture and storage. Widespread utilisation of such plants could help mitigate the negative impact of greenhouse gas emissions and climate change. Using the outcomes of the H2-IGCC project, the next generation of GTs will be more attractive compared to other competing technologies such as supercritical pulverised coal plants from techno-economic perspective. In addition, the techno-economic performance of the concerned plants will be further improved using advanced gas turbine technology such as G and H-class. One of the significant impacts of the project is that it could open up the energy market for IGCC with CCS in the future as it improved the commercial competitiveness compared to other power generation technologies with CCS. However, for this technology to be implemented, it is required that a political framework is in place with strong political commitment to intermediate and long term emissions reduction goals together with near term initiatives.

It should be highlighted that by enabling the technology of burning undiluted syngas derived from coal in advanced gas turbine, the total conversion efficiency was increased by a few percentage point. The increased efficiency could compensate a part of parasitic load of carbon capture process. The provided technology could allow coal to continue playing an important role in the security of energy supply in affordable way and help alleviate the dependency of Europe on external energy sources.

The project fully coped with the “Topic Energy 2008.6.1.4”. Steps required to deliver the expected impact correspond to the aims of the four technical Subproject constituting the proposal:

1) Combustion, aimed at investigating and testing improved combustion systems for H_2-rich syngas;

2) Materials, aimed at investigating and demonstrating the performance of the state of the art as well as innovative materials/coatings in novel operating conditions;

3) Turbomachinery, addressed to study compressor and turbine aerodynamics and aeroelasticity and turbine cooling system to identify feasible machinery modifications;

4) System Analysis, aimed at best integration of novel GT’s in IGCC plants taking technical, economical, control policies and life consumption aspects into account.

The industrial project partners, both OEMs and utility companies recognise the significant impact the success of the project had in helping to open up the market for IGCC, and in the future with CCS. In particular, the integrated approach used in the project will increase confidence and reduce deployment times for the new technologies developed in the project.
In order to achieve the aforementioned project’s impact, the System Analysis group provided the best integration of the novel gas turbine technology optimised for hydrogen-rich syngas operation in IGCC plants taking technical, economic, and control policies aspects into consideration.

The project has brought significant results in the process of the materials selection for the IGCC systems, and will help to ‘future-proof’ the gas turbine as fuels change and CCS is introduced. By addressing the key challenges of increased water vapour and corrosion flux on alloy/coating performance, coupled with the development of life prediction and NDE methods, the project has substantially reduced the risks taken in the design process for IGCC gas turbines. Validation of the materials developments and life prediction tools have been carried out in a rainbow test proposed within the program. This allowed for performance evaluation of materials and coatings in an actual gas turbine, thus minimizing the risk of unforeseen problems when introduced into service machines.

Through the early development of the next generation of protective coatings systems, the project results will see early exploitation in currently operating turbines, where they are expected to improve the reliability.

The industry partners have developed and qualified design tools for the design of new combustion systems for Syngas fuels. The main driver in the design was to eliminate the diluent which needs to be added to the fuel to

achieve low NOx emissions. Currently there is no commercial combustion system available which does not need any dilution.
While premixed systems which are the state-of-the-art for natural gas combustion offer the potential for low dilution or even no dilution, some concerns remain with respect to thermo-acoustic instabilities and flashback.

The OEM's will use the developed design tools that have been tested and qualified in the project. The evaluation and benchmarking of different approaches provided by different R&D partners was required to complete this complex task.

The partnership gathers universities, research centres, SME and large industries well representing the major actors involved in the field at European level. The specific competencies of the partners allowed facing all the problems, arising in the development phases of the project. The sharing of the results among the partners has been absolutely necessary to obtain the final objective. Despite tough competition, all stakeholders have a common and convergent interest in deploying and exploiting the actual potential of any gas turbine technology, as fully as possible and as soon as possible. The presence of large European industries already involved in development and management of IGCC plants grants the exploitation of project outcomes and lays down conditions for future large scale demonstration.

Impact on EU Policy Goals

By enabling the technology of burning undiluted syngas derived from coal in advanced gas turbine, the conversion efficiency will increase. The increased efficiency will compensate partly the part lost during the carbon capture process and bring the commercialisation of CCS closer to reality.

This will allow coal to continue playing an indispensable role in the security of energy supply in Europe. Currently, coal-fired power plants have a share of 29% of the electricity generation. EU dependence on imported energy will increase from the current 50% to 65% by 2030. Europe has abundant coal reserves, the exploitation of which will help alleviate the dependency of Europe on external sources.

In the meantime, with or without CCS, an IGCC plant produces significantly less pollutants than traditional coal-based power plants. EU greenhouse gas emissions will exceed the 1990 level by 2% in 2010 and by 5% in 2030. IGCC combined with CCS will help mitigate the negative impact of greenhouse gases (GHGs) and play an integral role in fighting climate change. The economic growth which now relies highly on energy provision will be sustainable over a much longer term.

CCS is identified by the European Strategic Energy Technology Plan (SET-Plan) as one of the promising technologies endorsed by the European Commission in reaching the goal of 20% CO2 reduction by 2020. Similar to many other novel technologies, CCS needs strong support from the EC to kick start what is defined as the "technology push" in combination with other market pull methods including the Emissions Trading Scheme and favourable regulatory regime. Industry needs the incentive and support from the EC.

The work within the H2-IGCC project brought the industry and research institutes closer together. This helped the transfer of knowledge from the industry to research institutes and vice versa. The project has foreseen closer cooperative relationship between the industry and academic partners during and beyond the project duration. This developed relationship will facilitate future cooperative partnerships and possibly in the next phase a full scale demonstration.

The target year of 2020 for CCS deployment is only achievable when different parts of the efficiency chain are improved in building near zero emission power plants (ZEP). According to the analysis of the SET-Plan, "If the maximum potential is realised, ZEP plants could potentially avoid up to 700 Mt/year CO2 in 2030, depending on the time of deployment of the technology. The corresponding maximum cumulative avoided CO_2 emissions for the period 2010 to 2030 would be up to 4.7 Gt".

On the international level, both the US and Japan have been working on clean coal technology and IGCC over the past years and China is now also focusing on the development of IGCC technology. The support and investment from the EU in the research of advanced gas turbine and clean coal technology has boosted the position of the European industry to the forefront. It has also enhanced the competitiveness of the European gas turbine industry and research community in the global market.

Dissemination of project results

ETN is responsible for the dissemination of project results.

The exploitation of the project results is as important as its research phases. The general principle has been to widely disseminate project interim results and final results to particularly gas turbine users and OEMs while respecting sensitive proprietary information. OEMs and gas turbine users will be able to refer to the results of the project and select the optimum IGCC plant configuration, and prepare for the next phase of full-scale demonstration.

Several tools have been used to disseminate information open to public:

- A **project website** has been established at the start of the project and maintained by ETN. Information such as project findings, background information, white papers, contacts and project reports can be found on the website. The website will be maintained up to two years after the end of the project duration so that stakeholders can still refer to the project for future work.

- **Annual reports** and have been prepared by the Coordinator with inputs from the subproject leaders. It reports on the technical progress, interim results and budgetary issues. The publishable annual reports and public **deliverables** are available on the project website.

- Other **printed materials** have been prepared to increase the visibility of the project and pave the way for future dissemination. These printed materials have been in the form of brochures and publishable reports providing results of the project. Targeted audience include users and researchers with expertise in various technical domains, e.g. combustion, materials and turbomachinery.

- At the end of the project, a dissemination session will be set up in conjunction with the ETN's International Gas Turbine Conference 2014. External stakeholders and the public will be invited to the conference, in which project results will be presented and discussed. Apart from its own network, ETN will carefully select participants to ensure a wide representation of the OEMs, gas turbine users, third party service providers and academics. SMEs and organisations from new Member States will be targeted.

- ETN Project Office has used its established contacts with technical magazines and journals to announce the launch of the project and publish the project results. At the same time, project partners have sought publication of their research findings within their individual WPs on respective technical journals and magazines.

- ETN Project office has made sure that project results have been presented in leading technical gas turbine tradeshows, i.e. ASME-IGTI, Power-Gen (see dissemination list below).

- Continuous dissemination of project progress and results through the ETN network during and beyond project duration.

The dissemination activities have been essentially carried out by ETN Project Office. The table in the next page summarises the dissemination activities, which is indicative and by no means an exhaustive list.

Type	**Possible activities**	**Target audience**	**Materials**	**Indicative timeframe**
Website Official	Background information, links to partners organisation, links to EC, related projects and FP7, publication	Public, researchers, gas turbine technology stakeholders (users, OEMs and research institutes)	Project overview, contacts, links, brochures, photographs, presentations, press release, project reports	2009 – 2015
Website confidential, Forum	Project proposal, partners directory, consortium agreement, status updates, project reports	Project partners	Copy of consortium agreement, copy of project proposal, Forum discussion, copy of deliverables, project status reports, other shared documents, news, meeting agenda, minutes, events	2009 – 2014
Tradeshow and exhibition, e.g. ASME and Power-Gen	Project progress and results	Public, gas turbine researchers and stakeholders	Project reports, posters, brochure	2009 - 2014
Publication in technical journals and magazines	Project Description, presentation of (interim and end) results	Public, gas turbine researchers and stakeholders	Project reports	2010 – 2014
Press release	Project Description, results	Public, gas turbine researchers and stakeholders	Photographs, charts, project reports	2009 – 2014
Cordis Magazine and website	Technology market place, events	Public, gas turbine researchers	Press release, conference invitation	2009 – 2014
Personal contact including press and journalists	Project Description, progress and results	Stakeholders through ETN network	Brochure, press release, posters	2009 – 2014
ETN Annual General Meetings and 5th + 6th International Gas Turbine Conferences	Interim and final results of the project	Gas turbine experts from the whole value chain, targeted stakeholders, EC and public	Interim and final reports, posters, brochure, presentations	2010 – 2014

In order to effectively disseminate the information and publishable results, ETN and partners have participated in the following selected events.

Event	Date & Location	Participation/Relevance
ETN Annual Workshop	October 2009, Copenhagen, Denmark	SP 1 - 4
International Conference on Power Engineering	16-20 November 2009, Kobe, Japan	SP 4 & 5
ETN AGM & Workshop	April 2010, Budapest, Hungary	All SPs
ASME Turbo Expo 2010	June 2010, Glasgow, Scotland, UK	SP 1 - 4
Powergen Europe 2010	June 2010, Amsterdam, The Netherlands	SP 4 & 5
Symp. (Int.) on Combustion	August 2010	SP 1
ICEPAG 2010 (US)	February 2010, Costa Mesa, US	All SPs
5th International Gas Turbine Conference	October 2010, Brussels, Belgium	All SPs
ETN AGM & Workshop	April 2011, Amsterdam, The Netherlands	All SPs
European Combustion Meeting	April 2011	SP 1
ASME Turbo Expo 2011	June 2011, Vancouver, Canada	SP 1 - 4
Powergen Europe 2011	June 2011, Milan, Italy	SP 4 & 5
ETN Annual Workshop	October 2011, Brighton, UK	SP 1 - 4
Congress of Gas Turbine Society of Japan	November 2011, Japan	SP 5
ETN AGM & Workshop	April 2012, Berlin, Germany	All SPs
Turbine Forum	April 2012, Nice, France	All SPs
NexTurbine 2012	May 2012, Shanghai, China	All SPs
3rd Gas Turbine Symposium	May 2012, Delft, The Netherlands	All SPs
ASME Turbo Expo 2012	June 2012, Copenhagen, Denmark	SP 1 - 4
Powergen Europe 2012	June 2012, Cologne, Germany	SP 4 & 5
Symp. (Int.) on Combustion	August 2012	SP 1
EVI – GTI Conference	October 2012, Florence, Italy	All SPs
6th International Gas Turbine Conference	October 2012, Brussels	All SPs
Gas to Power Conference 2013	February 2013, Brusssels, Belgium	All SPs
ETN AGM & Workshop	April 2013, Pisa, Italy	All SPs
European Combustion Meeting	April 2013	SP 1
ASME Turbo Expo 2013	June 2013, San Antonio, US	SP 1 - 4

Powergen Europe 2013	June 2013, Vienna, Austria	SP 4 & 5
ETN Annual Workshop	October 2013, London, UK	All SPs
Industrial Application of Gas Turbines (IAGT)	October 2013, Banff, Canada	All SPs
3rd Annual Gas Turbine World China Summit	October 2013, Shanghai, China	All SPs
Dutch Gas Turbine Association Annual Meeting	January 2013, Nieuwegein, The Netherlands	All SPs
AGM and Workshop	April 2014, Paris, France	All SPs
H2-IGCC project-end conference	May 2014, Brussels, Belgium	All SPs
7th International Gas Turbine Conference	October 2014, Brussels, Belgium	All SPs
ASME Turbo Expo 2014	June 2014, Dusseldorf, Germany	All SPs
Powergen Europe 2014	June 2014, Cologne, Germany	All SPs

Scientific papers of research findings have been produced during the project by partners.

- Modern Power Systems
- Diesels & Gas Turbine Worldwide
- Energy Industry Times
- American Society of Mechanical Engineers (ASME) Journals
- PowerGen
- ASM Advanced Materials
- Combined Cycle Journal
- Gas Turbo Technology
- Power Engineering
- Material Evaluation
- Gas Turbine World
- Practical Metallography
- Turbomachinery International
- Touch Briefings
- JOM – TMS
- Turbomachinery International
- Institution of Mechanical Engineers (IMechE) Journals
- AIAA Journals
- Proceedings of the Combustion Institute
- Combustion Science & Technology
- Combustion & Flame
- Combustion Theory and Modelling
- Flow, Turbulence and Combustion
- Journal of Sound and Vibration
- Applied Thermal Engineering

Exploitation of Results

Phase	Activities	2009	2010	2011	2012	2013	2014	2015	>2015
Phase 1	**Research & Development**								
Phase 2	**Proof of principle (lab-scale)**								
Phase 3	**Proof of concept (pilot)**								
Phase 4	Demonstration of prototype components on plant level								

Phase 1, 2 and 3 have been treated by the H2-IGCC project. In the phases of research & development and proof-of-principle existing issues are solved. The construction of a demonstration plant would be the following step sometime after the completion of the project.

Through the participation of the industry, knowledge developed within H2-IGCC will improve their products. Operators of gas turbine based power generation plants (i.e. Enel, EDF, Nuon) will be able to select best-of-class IGCC schemes with Carbon Capture & Storage (CCS) .

EDF will use the results of the project to build its own opinion on technical feasibility of premix mode avoiding dilution to meet the NOx emission limitations. When this is demonstrated even in laboratory scale, it will make clearer the potential advantage for pre-combustion CO_2 capture technology for which the cost of avoided CO2 would be lower.

Nuon operates an IGCC plant (Buggenum) and is in a project to develop a new IGCC plant in the North of the Netherlands (Magnum-project). By adding the CCS-unit the hydrogen content in the syngas will increase, adding challenges to the design of the syngas burner system, which have been studied and demonstrated in the H2-IGCC project. The H2-IGCC project results could be, therefore, incorporated in either Nuon's Magnum-project or a future IGCC power plant.

Enel is carrying on research projects on all the available technologies for CCS. The H2-IGCC project will provide useful information to evaluate the competitiveness of IGCC with other CCS technologies for large scale electricity production, taking into account cycle efficiency, engine reliability and endurance, environmental compatibility. The results of the project will be used to evaluate the feasibility of undiluted hydrogen combustion and to assess the compatibility of new materials with the working conditions of GTs in IGCC applications.

Research institute and university partners will use H2-IGCC results for further R&D, engineering and educational activities. New and accurate turbulent combustion models, dedicated to the present & future class of fuels, will be developed for use in design procedures.

Generic (combustion & materials) property data will be of general value and an indispensable pre-requisite for the design of plant components in Zero Emission Power Plant Concepts using Pre-Combustion Fuel-Decarbonization.

OEMs participanting in the project will use the experience and deliverables of the consortium to demonstrate and qualify new design tools.

Ansaldo has demonstrated modified burner designs on a prototype scale able to operate on undiluted hydrogen rich syngas with low emissions which will be the basis for implementation in the next generation of gas turbines for IGCC.

E.ON will be involved in the applied research activities for the combustion of high hydrogen syngas and will investigate more specifically the operational aspects and risk levels associated with various fuel mixtures. E.ON is committed to use the knowledge acquired throughout this project to guide & support the development of future technologies and products for the benefit of gas turbine users and the general community.

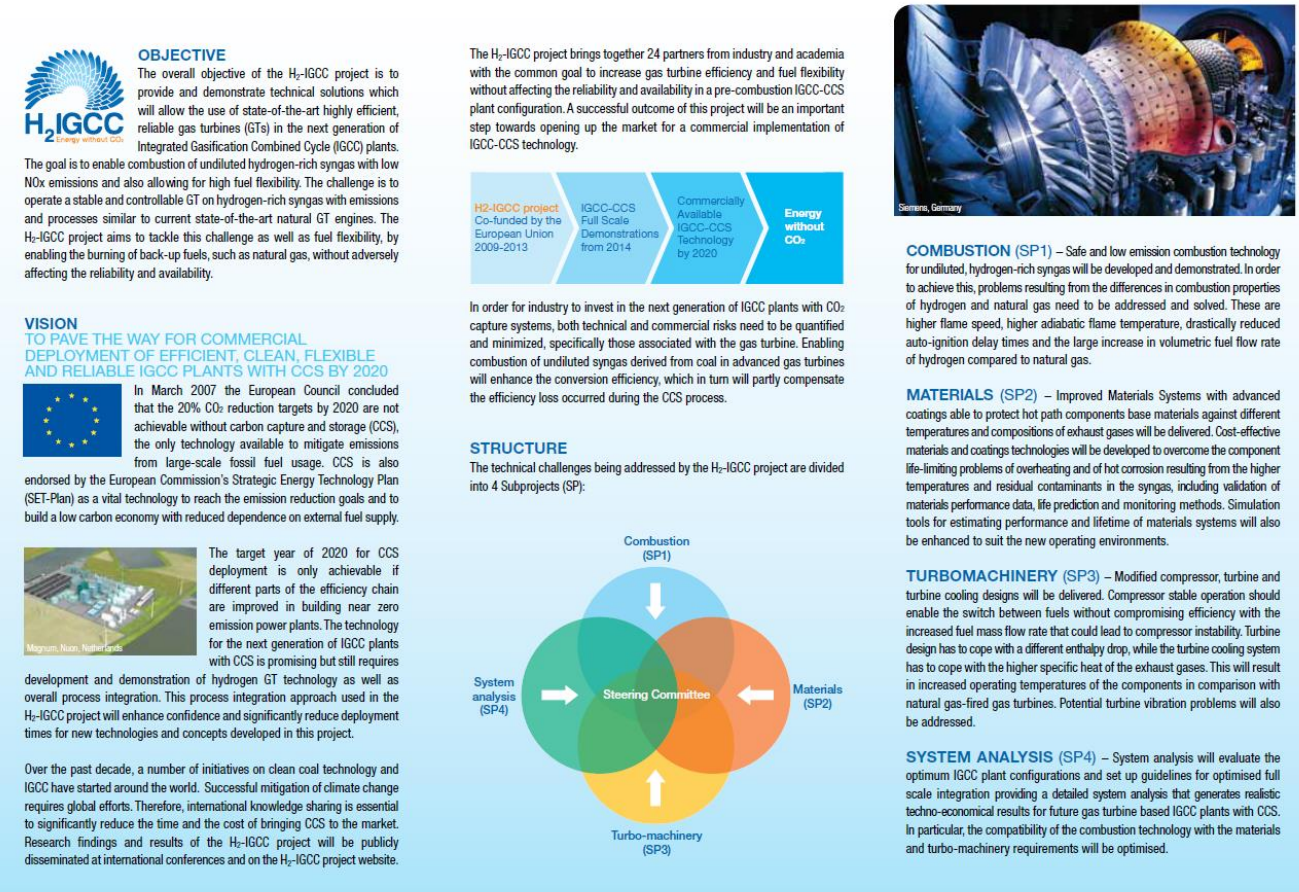
Siemens will utilise the design tools to investigate new concepts for syngas combustion. Special emphasis will be put on the prediction of flashback resistance and thermo-acoustic stability which limits the operational range of the engine.

A successful implementation of the developed technical solutions by the industry partners of this project is expected to make possible the deployment of high efficiency gas turbines in competitive IGCC plants with Carbon Capture and Storage technology targeted for the year 2020.

1.5. Project website address

http://www.h2-igcc.eu/default.aspx

Figure 6 - Project logo



OBJECTIVE

The overall objective of the H_2-IGCC project is to provide and demonstrate technical solutions which will allow the use of state-of-the-art highly efficient, reliable gas turbines (GTs) in the next generation of Integrated Gasification Combined Cycle (IGCC) plants. The goal is to enable combustion of undiluted hydrogen-rich syngas with low NOx emissions and also allowing for high fuel flexibility. The challenge is to operate a stable and controllable GT on hydrogen-rich syngas with emissions and processes similar to current state-of-the-art natural GT engines. The H_2-IGCC project aims to tackle this challenge as well as fuel flexibility, by enabling the burning of back-up fuels, such as natural gas, without adversely affecting the reliability and availability.

VISION

TO PAVE THE WAY FOR COMMERCIAL DEPLOYMENT OF EFFICIENT, CLEAN, FLEXIBLE AND RELIABLE IGCC PLANTS WITH CCS BY 2020

In March 2007 the European Council concluded that the 20% CO_2 reduction targets by 2020 are not achievable without carbon capture and storage (CCS), the only technology available to mitigate emissions from large-scale fossil fuel usage. CCS is also endorsed by the European Commission's Strategic Energy Technology Plan (SET-Plan) as a vital technology to reach the emission reduction goals and to build a low carbon economy with reduced dependence on external fuel supply.

Magnum, Nuon, Netherlands

The target year of 2020 for CCS deployment is only achievable if different parts of the efficiency chain are improved in building near zero emission power plants. The technology for the next generation of IGCC plants with CCS is promising but still requires development and demonstration of hydrogen GT technology as well as overall process integration. This process integration approach used in the H_2-IGCC project will enhance confidence and significantly reduce deployment times for new technologies and concepts developed in this project.

Over the past decade, a number of initiatives on clean coal technology and IGCC have started around the world. Successful mitigation of climate change requires global efforts. Therefore, international knowledge sharing is essential to significantly reduce the time and the cost of bringing CCS to the market. Research findings and results of the H_2-IGCC project will be publicly disseminated at international conferences and on the H_2-IGCC project website.

The H_2-IGCC project brings together 24 partners from industry and academia with the common goal to increase gas turbine efficiency and fuel flexibility without affecting the reliability and availability in a pre-combustion IGCC-CCS plant configuration. A successful outcome of this project will be an important step towards opening up the market for a commercial implementation of IGCC-CCS technology.

H2-IGCC project Co-funded by the European Union 2009-2013 → IGCC-CCS Full Scale Demonstrations from 2014 → Commercially Available IGCC-CCS Technology by 2020 → Energy without CO_2

In order for industry to invest in the next generation of IGCC plants with CO_2 capture systems, both technical and commercial risks need to be quantified and minimized, specifically those associated with the gas turbine. Enabling combustion of undiluted syngas derived from coal in advanced gas turbines will enhance the conversion efficiency, which in turn will partly compensate the efficiency loss occurred during the CCS process.

STRUCTURE

The technical challenges being addressed by the H_2-IGCC project are divided into 4 Subprojects (SP):

Combustion (SP1)
Materials (SP2)
Turbo-machinery (SP3)
System analysis (SP4)
Steering Committee

Siemens, Germany

COMBUSTION (SP1) – Safe and low emission combustion technology for undiluted, hydrogen-rich syngas will be developed and demonstrated. In order to achieve this, problems resulting from the differences in combustion properties of hydrogen and natural gas need to be addressed and solved. These are higher flame speed, higher adiabatic flame temperature, drastically reduced auto-ignition delay times and the large increase in volumetric fuel flow rate of hydrogen compared to natural gas.

MATERIALS (SP2) – Improved Materials Systems with advanced coatings able to protect hot path components base materials against different temperatures and compositions of exhaust gases will be delivered. Cost-effective materials and coatings technologies will be developed to overcome the component life-limiting problems of overheating and of hot corrosion resulting from the higher temperatures and residual contaminants in the syngas, including validation of materials performance data, life prediction and monitoring methods. Simulation tools for estimating performance and lifetime of materials systems will also be enhanced to suit the new operating environments.

TURBOMACHINERY (SP3) – Modified compressor, turbine and turbine cooling designs will be delivered. Compressor stable operation should enable the switch between fuels without compromising efficiency with the increased fuel mass flow rate that could lead to compressor instability. Turbine design has to cope with a different enthalpy drop, while the turbine cooling system has to cope with the higher specific heat of the exhaust gases. This will result in increased operating temperatures of the components in comparison with natural gas-fired gas turbines. Potential turbine vibration problems will also be addressed.

SYSTEM ANALYSIS (SP4) – System analysis will evaluate the optimum IGCC plant configurations and set up guidelines for optimised full scale integration providing a detailed system analysis that generates realistic techno-economical results for future gas turbine based IGCC plants with CCS. In particular, the compatibility of the combustion technology with the materials and turbo-machinery requirements will be optimised.

Figure 7 - Project brochure

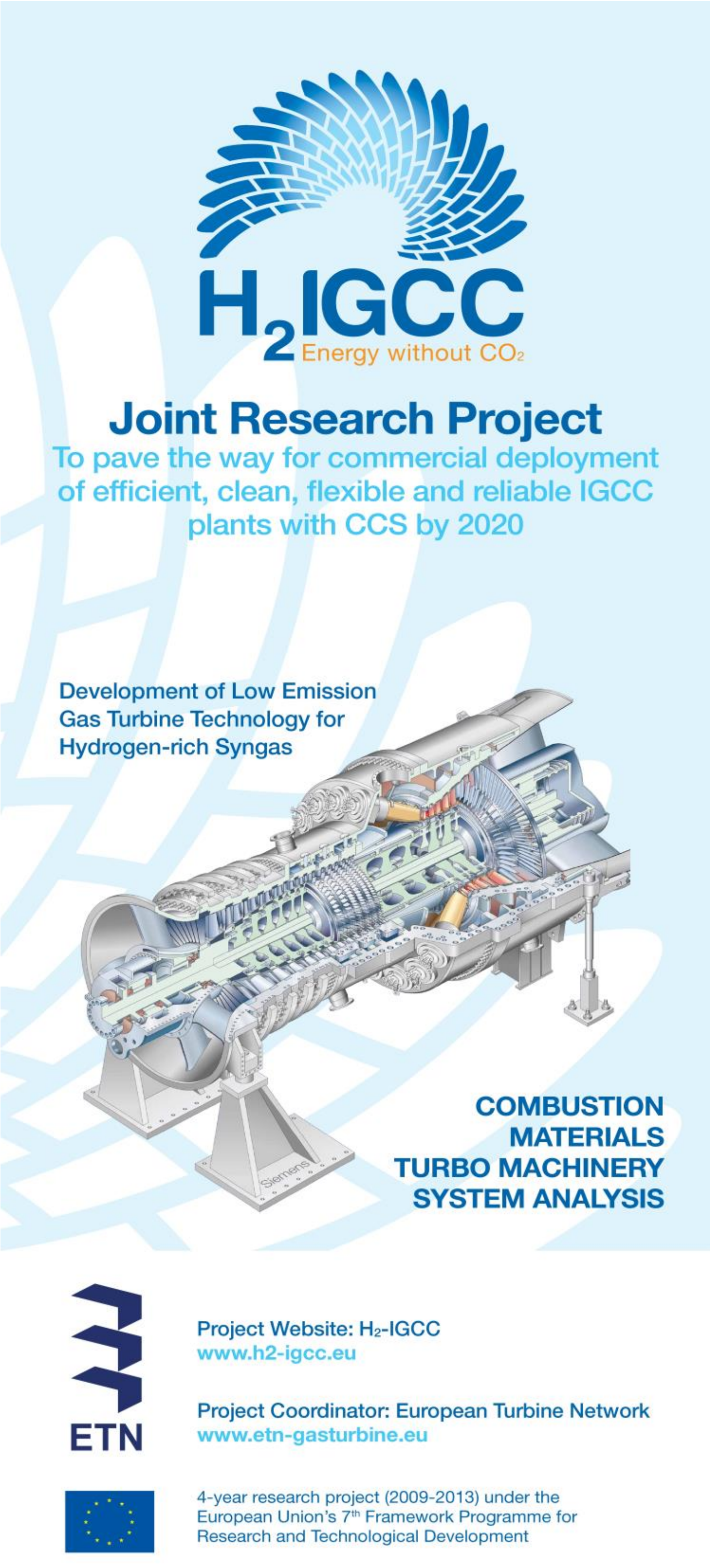


Figure 8 - Project poster

List of all beneficiaries

Number	Organisation	Country	Name	Email	Phone number 1
1	European Turbine Network a.i.s.b.l (ETN)	Belgium	**Christer Bjorkqvist**	cb@etn-gasturbine.eu	02 646 1577
2	Paul Scherrer Institute (PSI)	Switzerland	**Peter Jansohn**	peter.jansohn@psi.ch	+41 (56) 310 2871
3	Deutsche Zentrum für Luft- und Raumfahrt (DLR)	Germany	**Peter Griebel**	peter.griebel@dlr.de	
4	Ansaldo Energia (AEN)	Italy	**Carla Mao**	carla.mao@ari.ansaldo.it	+39 010 655 3356
4	Ansaldo Energia (AEN)	Italy	**Domenico Zito**	domenico.zito@aen.ansaldo.it	
5	Cenaero	Belgium	**Etienne Lorriaux**	etienne.lorriaux@cenaero.be	
6	Technical University of Eindhoven (TU/e)	The Netherlands	**Rob Bastiaans**	r.j.m.bastiaans@tue.nl	+31 402 474 836
7	Electricite De France (EDF)	France	**Mohamed Kanniche**	mohamed.kanniche@edf.fr	
8	Forschungszentrum Jülich (JULICH)	Germany	**Daniel E. Mack**	d.e.mack@fz-juelich.de	+49 (2461) 61-2971
9	ERSE	Italy	**Federico Cernuschi**	federico.cernuschi@rse-web.it	+39 0239924577
10	University Roma TRE (RO3)	Italy	**Giovanni Cerri**	cerri@uniroma3.it	+39 (06) 551 73 251
11	University of Sussex (UoS)	UK	**Rossana Dowsett**	r.l.dowsett@sussex.ac.uk	
12	Siemens	Germany	**Lukasz Panek**	lukasz.panek@siemens.com	
13	Laborelec (LBE)	Belgium	**Hannes Laget**	hannes.laget@laborelec.com	
14	Cardiff University (CU)	UK	**Prof. Phil Bowen**	bowenpj@cardiff.ac.uk	+44 292 087 4292
15	Flame Spray Hungary	Hungary	**Alessandro Moscatelli**	alessandro.moscatelli@flamespray.org	
16	RWTH Aachen	Germany	**Herwart Hoenen**	hoenen@ist.rwth-aachen.de	
17	Cranfield University	UK	**Prof. John Oakey**	j.e.oakey@cranfield.ac.uk	+44 123 754 253

18	Enel	Italy	**Stefano Sigali**	stefano.sigali@enel.it	
19	University of Sheffield (USFD)	UK	**Prof. Panos Tsakiropoulos**	p.tsakiropoulos@sheffield.ac.uk	+44 114 222 59 60
20	University of Stavanger (UiS)	Norway	**Mohsen Assadi**	mohsen.assadi@uis.no	
20	University of Stavanger (UiS)	Norway	**Peter Breuhaus**	peter.breuhaus@iris.no	
21	Nuon	The Netherlands	**Chris Lappee**	chris.lappee@nuon.com	+31 (6) 1515 9509
21	Vattenfall	The Netherlands	**Mareike Schneider**	mareike.schneider@vattenfall.de	
22	University of Genova (UNIGE-DIMSET)	Italy	**Ferruccio Pittaluga**	ferruccio.pittaluga@unige.it	
23	E.ON Engineering	UK	**Catherine Goy**	catherine.goy@eon.com	+44 (0) 2476 192721
24	National University of Ireland Galway (NUI)	Ireland	**Henry Curran**	henry.curran@nuigalway.ie	
25	City University London	UK	**Abdulnaser Sayma**	a.sayma@city.ac.uk	

2. Use and dissemination of foreground

A plan for use and dissemination of foreground (including socio-economic impact and target groups for the results of the research) shall be established at the end of the project. It should, where appropriate, be an update of the initial plan in Annex I for use and dissemination of foreground and be consistent with the report on societal implications on the use and dissemination of foreground (section 4.3 – H).

The plan should consist of:

- Section A

  This section should describe the dissemination measures, including any scientific publications relating to foreground. **Its content will be made available in the public domain** thus demonstrating the added-value and positive impact of the project on the European Union.

- Section B

  This section should specify the exploitable foreground and provide the plans for exploitation. All these data can be public or confidential; the report must clearly mark non-publishable (confidential) parts that will be treated as such by the Commission. Information under Section B that is not marked as confidential **will be made available in the public domain** thus demonstrating the added-value and positive impact of the project on the European Union.

Section A (public)

This section includes two templates

- Template A1: List of all scientific (peer reviewed) publications relating to the foreground of the project.
- Template A2: List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project. Updates are possible at any time.

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[4] (if available)	Is/Will open access[5] provided to this publication?
	An EU initiative for future generation of IGCC power plants using hydrogen-rich syngas: Simulation results for the baseline configuration	*Mohammad Mansouri Majoumerd, Stavanger University*	*Applied Energy*	*No 99, November 2012*	*Elsevier*	*Worldwide Also online*	*2012*	*280-290*	*http://www.sciencedirect.com/science/article/pii/S0306261912003923*	
	An experimental and detailed chemical kinetic modeling study	*Alan Kéromnès, NUI Galway*	*Combustion and Flame*	*No 160, June 2013*	*Elsevier*	*Worldwide Also online*	*2013*	*995-1011*	*http://www.sciencedirect.com/science/article/pii/S001021801300*	

[4] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[5] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

	of hydrogen and syngas mixture oxidation at elevated pressures								*0023*	
	The effect of elevated pressures on the laminar burning velocity of methane + air mixtures	*Mayuri Goswami, TU Eindhoven*	*Combustion and Flame*	*No 160, June 2013*	*Elsevier*	*Worldwide Also online*	*2013*	*1627-1635*	*http://www.sciencedirect.com/science/article/pii/S0010218013001326*	
	This thesis is under development and will be available in June 2014.	*Mohammad Mansouri Majoumerd, Stavanger University*	*Doctoral thesis*		n.a	n.a		n.a	n.a	
	Gas turbine based power generation with CO2 capture, Opportunities and challenges	*Nikolett Sipöcz Stavanger University*	*Doctoral thesis*	*November 2011*	Univ. of Stavanger	Norway	*2011*	36-40; 61-65	ISBN 978-82-7644-465-0	
	Laminar burning velocity of lean H2/CO mixtures at elevated pressure using the heat flux method	*Mayuri Goswami, TU Eindhoven*	*International Journal of Hydrogen Energy*	*12 per year*	ELsevier		*2013*	(39)1485-1498	http://dx.doi.org/10.1016/j.ijhydene.2013.10.164	No
	Numerical simulations of flat laminar premixed methane-air flames at elevated pressure.	*Mayuri Goswami, TU Eindhoven*	*Combustion Science and Technology*	*12 per year*	Taylor & Francis		*2014*	Accepted		No
	Towards numerical simulation of turbulent hydrogen combustion based on flamelet generated manifolds with OpenFOAM	*Alessio Fancello, TU Eindhoven*	*American Institute of Physics Journal*	*1558, 168*	AIP	Rhodos (Greece)	2013	4	*http://scitation.aip.org/content/aip/proceeding/aipcp/10.1063/1.4825447*	no

	. *Numerical simulation of turbulent combustion using RANS - LES models and flamelet generated manifolds*	*Alessio Fancello, TU Eindhoven*	*ECM proceedings*		ECM	Cardiff (UK)	2011	5	*http://purl.tue.nl/395987968812167*	
	Turbulent Flame Speed as an Indicator for Flashback Propensity: An Example for Wet Gas Turbine Applications		*Journal of Engineering for Gas Turbines and Power*							
	Estimation of performance variation of future generation IGCC with coal quality and gasification process – Simulation results of EU H2-IGCC project	*Mohammad Mansouri Majoumerd, University of Stavanger*	*Applied Energy*	*No 113*	Elsevier	*Worldwide Also online*	*2013*	*452-462*	*http://www.sciencedirect.com/science/article/pii/S0306261913006181*	
	Experimental and modeling study of effect of elevated pressure on lean high-hydrogen syngas flames.	*Mayuri Goswami, TU Eindhoven*	*Proceedings of the Combustion Institute*	*Biennial*	Elsevier		*2014*	Submitted		*No*
	Laminar burning velocities at elevated pressures using the heat flux method	*Mayuri Goswami, TU Eindhoven*	*PhD Thesis*		TU/e		*2014*	Approved	ISBN: 978-90-386-3564-4	*No*
	Fireside issues in advanced power generation systems	*Nigel Simms, Cranfield University*	*Materials Science and Technology*	*Vol. 29 (7)*	Maney	London / on-line	*2013*	804-812	DOI 10.1179/1743284712Y.0000000133	

	Hot Corrosion Resistance of Gas Turbine Materials in Combusted Syngas Environments	*Joy Sumner, Cranfield University*	*Materials at High Temperature*		Maney		*in press*	In press	In press	
	Lifetime Modelling of Gas Turbine Materials in Novel, H_2-Rich Syngas Environments	*Joy Sumner, Cranfield University*	*Proceedings of the 10th Liege Conference*				*2014*	Submitted		
	High Temperature Corrosion in Gas Turbines: Data Collection and Modelling	*Nigel Simms, Cranfield University*	*Proceedings of the 10th Liege Conference*				*2014*			
	Hot Corrosion Modelling of Gas Turbine Materials in Novel Combusted Syngas Environments	*Joy Sumner, Cranfield University*	*Proceedings of the ISHOC Conference*				*2014*	In press		
	Modelling of Hot Corrosion Resistance for Gas Turbine Materials Systems in Novel Combusted Syngas Environments	*Joy Sumner, Cranfield University*	*Proceedings of the 7th International Gas Turbine Conference*				*2014*			
	Solid particle erosion of TBCs: jet tester modelling and erosion forecasts	*RSE*	*Advanced ceramic Coatings and Materials for Extreme Environments*	*1 per year*	Wiley& Sons	USA	*2014*	Submitted		
	Behaviour of Alloys and Coatings in Environment Relevant to Gas-Turbines Operating with Hydrogen-Rich Syngas Fuels	*Wojciech, Nowak* *FZJ Jülich*	*PhD Thesis*		RWTH Aachen		*2014*	To be submitted in June 2014		
	Effect of Processing Parameters on MCrAlY	*Wojciech, Nowak*	*Surface and Coatings*		Elsevier		*2014*	Submitted		

	Bondcoat Roughness and Lifetime of APS-TBC Systems	*FZJ Jülich*	*Technology*							
	Investigation of Flame Stabilization in a High-Pressure Multi-Jet Combustor by Laser Measurement Techniques	*Oliver Lammel* *DLR*	*Proc. ASME Turbo Expo 2014, Power for Land, Sea and Air*				*2014*			
	Design of Axial Compressors for fuel flexibility	*Pascal Nucara-University of Sussex*	*PhD thesis*		University of Sussex		*2014*	Approved		
	Compressor Re-staggered Configuration for Conventional F-Class Gas Turbine Fired With H2-rich Syngas	*City University London*	*ASME Journal of Propulsion and Power*		City University London		*2014*	Submitted		

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES							
Type of activities[6]	Main leader	Title	Date/Period	Place	Type of audience[7]	Size of audience	Countries addressed
Brochure distributed at 30+ events between 2009-2014	*ETN*	*H2-IGCC Brochure*	*2009-2014*	*n.a.*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other*	*2000+*	*Worldwide*
Articles in ETN Newsletter	*ETN*	*H2-IGCC Project*	*In 15+ editions between 2009-2014*	*Web, e-mail*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other*	*250+*	*Worldwide*
Article in Gas Turbine World	*Enel*	*Fusina puts hydrogen gas turbine to test*	*March-April 2010*	*Web, printed copy*	*Scientific Community (higher*	*10000+*	*Worldwide*

6 A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

7 A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

					education, Research), Industry, media		
Article in Modern Power Systems	ETN	A project to develop turbine technologies for IGCC+CCS	June 2010	Web, printed copy	Scientific Community (higher education, Research), Industry, media	12000+	Worldwide
Project Outline in Programme Brochure " International Gas Turbine Conference"	ETN	Low Emissions Gas Turbine Technology for Hydrogen-rich Syngas	October 2010	Web, printed Copy	Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias	250+	Worldwide
Article in Global Gas Turbine News	ETN	Low Emission Gas Turbine Technology for Hydrogen-rich Syngas	December 2010	Web, printed copy	Scientific Community (higher education, Research), Industry	5000+	Worldwide
Paper and Presentation at "International Gas Turbine Conference 2010, Brussels"	Nuon	H2-IGCC: Low Emission Gas Turbine Technology for Hydrogen-rich Syngas EU-funded project to develop turbine technologies for IGCC with CCS	October 2010	Brussels, Belgium	Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias	200+	Worldwide
Paper and Presentation at "International Gas Turbine Conference 2010, Brussels"	NUIG, DLR	Ignition delay time measurements and validation of reaction mechanism for hydrogen at gas turbine relevant conditions	October 2010	Brussels, Belgium	Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias	200+	Worldwide

Presentation at the 3rd ISJPPE Conference	*Sussex University*	*The role of Numerical models in the prediction of compressor performance and stability*	*September 2010*	*Nanjing, China*	*Scientific Community (higher education, Research), Industry*	*50+*	*Wordwide*
Poster Presentation at "5th International Gas Turbine Conference 2010"	*TU Eindhoven*	*High Hydrogen Syngas Combustion for IGCC Gas Turbines*	*27-28 October 2010*	*Brussels, Belgium*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*200+*	*Worldwide*
Poster Presentation at "5th International Gas Turbine Conference 2010"	*TU Eindhoven*	*Flame Speed Measurement and Chemical Reaction Mechanism of High-H2 Syngas-Air Mixtures*	*27-28 October 2010*	*Brussels, Belgium*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*200+*	*Worldwide*
Expo at "5th International Gas Turbine Conference 2010"	*ETN*	*n.a.*	*27-28 October 2010*	*Brussels, Belgium*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*160*	*Worldwide*
Article in "The Energy Industry Times"	*ETN*	*From birth control to recession*	*November 2010*	*Printed copy, online*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*		*Worldwide*
5th European Combustion Meeting	*TU Eindhoven*	*Syngas combustion at high pressure*	*2011*	*Cardiff, UK*	*Scientific Community*		*Worlwide*

7th US National Technical Meeting of the Combustion Institute	*NUIG*	*Detailed Chemical Kinetic Model for H2 and H2/CO (Syngas) Mixtures at Elevated Pressure*	*March 2011*	*Georgia, USA*	*Scientific Community (higher education, Research), Industry*		*Worldwide*
Paper and Presentation at "ASME Turbo Expo 2011"	*University of Stavanger*	*Development of H2-rich syngas fuelled GT for future IGCC power plants – establishment of a baseline*	*6-10 June 2011*	*Vancouver, Canada*	*Scientific Community (higher education, Research), Industry*	*3000+*	*Worldwide*
Presentation at ETN AGM and Workshop 2011	*ETN, PSI*	*H2-IGCC Project Update*	*30 March 2011*	*Budapest, Hungary*	*Scientific Community (higher education, Research), Industry*	*65*	*European Union*
Presentation at "Turbo Power Conference"	*ETN*	*How to Influence and Effectively Develop Technology and Research in the European Arena"*	*13-14 April 2011*	*Gothenburg, Sweden*	Scientific Community		*Sweden, European Union*
Presentation at "EU-GCC Clean Energy Network Meeting"	*ETN*	*European Cooperation in Gas Turbine Technology: European Turbine Network & H2-IGCC project*	*11-12 May 2011*	*Brussels, Belgium*	*Scientific Community (higher education, Research), Industry, Policy makers*		*European Union*
Proceedings of the 7th OpenFOAM Workshop,	*Alessio Fancello, TU Eindhoven*	*RANS and LES of turbulent combustion based on flamelet generated manifolds,*	*June 2011*	*State College (PA - USA)*	Scientific Community	*400+*	*Worldwide*
Papers and Presentation at "23rd ICDERS Conference"	*TU Eindhoven*	*Effect of Elevated Pressures on Laminar Burning*	*24-29 July 2011*	*Irvine, USA*	*Scientific Community (higher*		*Worldwide*

		Velocity of Methane+Air Mixtures using Heat Flux			*education, Research), Industry*		
Presentation at ETN October Workshop 2011	*ETN, University of Stavanger*	*H2-IGCC Project Update*	*12 October 2011*	*Brighton, UK*	*Scientific Community (higher education, Research), Industry*	*75*	*European Union*
Article in "Energie Rondschau"	*PSI*	*Halbzeit auf den Weg zur neuen Generation von Gaskraftwerken*	*2012*	*Printed copies*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers*		*Switzerland*
Paper and Presentation at "36th International Conference and Expo on Advanced Ceramics and Composites"	*FZ Julich*	*$Gd_2Zr_2O_7$-YSZ composites for high temperature corrosion resistant thermal barrier coatings*	*22-27 January 2012*	*Daytona Beach, US*	*Scientific Community (higher education, Research), Industry*		*Worldwide*
Presentation at "ETN AGM and Workshop 2012"	*ETN, PSI*	*H2-IGCC Project Update*	*17 April 2012*	*Berlin, Germany*	*Scientific Community (higher education, Research), Industry*	*75*	*European Union*
Paper and Presentation at "ASME Turbo Expo 2012"	*University of Sussex*	*Effects of using H_2-rich syngas in industrial gas turbines while maintaining fuel flexibility on a multistage axial compressor design*	*11-15 June 2012*	*Copenhagen, Denmark*	*Scientific Community (higher education, Research), Industry*	*3000+*	*Worldwide*

Proceedings of the 7th OpenFOAM Workshop,	*Alessio Fancello, TU Eindhoven*	*A flamelet generated manifolds lookup table tool for premixed turbulent combustion*	*June 2012*	*Darmstadt (Germany)*	Scientific Community	*400+*	*Worldwide*
Paper and Presentation at "ASME Turbo Expo 2012"	*University of Stavanger, University of RO3*	*Impact of fuel flexibility needs on a Selected GT performance in IGCC application*	*11-15 June 2012*	*Copenhagen, Denmark*	*Scientific Community (higher education, Research), Industry*	*3000+*	*Worldwide*
Presentation at "ASME Turbo Expo 2012"	*ETN*	*H2-IGCC Project Update*	*11-15 June 2012*	*Copenhagen, Denmark*	*Scientific Community (higher education, Research), Industry*	*3000+*	*Worldwide*
*Paper and Presentation at "*NAFEMS Multiphysic 2012*"*	*Cenaero*	*Conjugate Heat Transfer analysis of a cooled turbine blade*	*16-17 October 2012*	*Frankfurt, Germany*	*Scientific Community (higher education, Research), Industry*		*Europe*
Expo at "6th International Gas Turbine Conference 2012"	*ETN*	*n.a.*	*17-18 October 2012*	*Brussels, Belgium*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*170*	*Worldwide*
Presentation at "International Seminar on Gasification"	*University of Stavanger*	*Low emission GT Techn. for H2 rich syngas in Integrated Gasification Combined Cycle*	*18-19 October 2012*	*Stockholm, Sweden*	*Scientific Community (higher education, Research), Industry*	*200*	*Europe*
Presentation at "TU Delft Gas Turbine	*ETN*	*The energy sector: An electrifying*	*31 May 2012*	*Delft, The Netherlands*	*Scientific Community*	*40*	*TU Delft students and professors,*

Conference”		*working environment*			*(higher education, Research), Industry, students*		*Dutch Industry*
Presentations at “NexTurbine 2012 Conference”	*ETN, University of Sussex, University of Stavanger, TU Eindhoven*	*European IGCC-CCS Development and Introduction to the H2-IGCC Project*	*23-24 May 2012*	*Shanghai, China*	*Scientific Community (higher education, Research), Industry, Policy makers, Medias*	*100*	*Worldwide, China*
Presentation at “ International combustion symposium”	*TU Eindhoven*	*Heat flux method workshop*	*July 2012*	*Warsaw, Poland*	Scientific Community		*???*
Presentation at Internal GDF-Suez meeting	*Laborelec*	*Low Emission Gas Turbine Technology for Hydrogen-rich Syngas*	*15 November 2012*	*Brussels, Belgium*	*Industry*		*GDF Suez employees*
Article on the PSI website	*PSI*	*All fired up about lower CO2*	*January 2013*	*Online*	*Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*n.a.*	*PSI, Worldwide*
Presentation at ”ETN AGM and Workshop 2013”	*ETN, DLR*	*H2-IGCC Project Update*	*16 April 2013*	*Berlin, Germany*	*Scientific Community (higher education, Research), Industry*	*85*	*European Union*
Proceedings of the 14th International Conference on Numerical Combustion,SIAM	*Alessio Fancello, TU Eindhoven*	*Numerical simulation of turbulent hydrogen combustion based on flamelet generated*	*April 2013*	San Antonio (USA)	Scientific Community	250+	*Worldwide*

		manifolds with Openfoam.					
Proceedings of the 8th OpenFOAM Workshop	*Alessio Fancello, TU Eindhoven*	*Towards numerical simulation of turbulent hydrogen combustion based on flamelet generated*	*June 2013*	*Jeju (South Korea)*	Scientific Community	*250+*	*Worldwide*
Paper and Presentation at "ASME Turbo Expo 2013"	*University of Roma Tre*	*General Method for the Development of Gas Turbine Based Plant Simulators: An IGCC Application*	*3-7 June 2013*	*San Antonio, TX, US*	*Scientific Community (higher education, Research), Industry*	*3000+*	*Worldwide*
Paper and Presentation at "ASME Turbo Expo 2013"	*University of Roma Tre*	*Steam Cycle Simulator for CHP Plants*	*3-7 June 2013*	*San Antonio, TX, US*	*Scientific Community (higher education, Research), Industry*	*3000+*	*Worldwide*
Paper and Presentation at "ASME Turbo Expo 2013"	*University of Roma Tre*	*Compressor Modifications for 300 MW IGCC Gas Turbine Stable Behavior*	*3-7 June 2013*	*San Antonio, TX, US*	*Scientific Community (higher education, Research), Industry*	*3000+*	*Worldwide*
Presentation at European combustion meeting	*TU Eindhoven*	*Kinetic studies using laminar flames workshop*	*25-28 June 2013*	*Lund, Sweden*	*Scientific Community (higher education, Research), Industry*	*500+*	*Worldwide*
Presentation at 24th International Colloquium on Dynamics of Explosions and Reactive Systems (ICDERS)	*TU Eindhoven*	*Laminar burning velocity of H2/CO flames at elevated pressure using Heat Flux Method*	*28 July – 2 August 2013*	*Taipei, Taiwan*	*Scientific Community*		*Worldwide*
Presentation	*TU*	*Numerical*	*28 July – 2*	*Taipei, Taiwan*	*Scientific*		*Worldwide*

at 24th ICDERS	*Eindhoven*	*simulations of flat laminar premixed CH4/air flames at elevated pressure using the heat flux method.*	*August 2013*		*Community*		
Investigation of Flame Stabilization in a High-Pressure Multi-Jet Combustor by Laser Measurement Techniques	*Oliver Lammel* *DLR*	*Proc. ASME Turbo Expo 2014, Power for Land, Sea and Air*				*2014*	
Proceedings of the ETN 2014 Conference	*Alessio Fancello, TU Eindhoven*	*On hydrogen addition effects in turbulent combustion using Flamelet Generated Manifold technique*	*October 2014*	Brussels (Belgium)	Scientific Community	300+	*Worldwide*
Paper accepted to "ASME Turbo Expo 2014"	*University of Roma Tre*	*Expander Models for a Generic 300 MW F Class Gas Turbine for IGCC*	*June 16-20, 2014*	*Düsseldorf, Germania*	*Scientific Community (higher education, Research), Industry*	*3000+*	*Worldwide*
Turbulent combustion modeling using Flamelet Generated Manifolds for gas turbine applications in OpenFOAM.	*Alessio Fancello, TU Eindhoven*	*ASME Turbo Expo series*	*n.a.*	ASME	Dusseldorf (Germany)	2014	9
Presentation at Microscopy of Oxidation 9	*Cranfield University*	*Hot Corrosion Resistance of Gas Turbine Materials in Combusted Syngas Environments*	*15th April 2014*	*Nottingham, UK*	*Scientific Community, Industry*	*100+*	*Worldwide*
Poster presentation at 10th Liege Conference	*Cranfield University*	*Lifetime Modelling of Gas Turbine*	*14th-17th September*	*Liege, Belgium*	*Scientific Community,*	*To present*	*Worldwide*

		Materials in Novel, H_2-Rich Syngas Environments	*2014*		*Industry*		
Presentation at 10th Liege Conference	*Cranfield University*	*High Temperature Corrosion in Gas Turbines: Data Collection and Modelling*	*14th-17th September 2014*	*Liege, Belgium*	*Scientific Community, Industry*		*Worldwide*
Presentation at ISHOC	*Cranfield University*	*Hot Corrosion Modeling of Gas Turbine Materials in Novel Combusted Syngas Environments*	*23rd-27th June 2014*	*Hakodate, Japan*	*Scientific Community, Industry*		*Worldwide*
Presentation at ETN Conference (7th International Gas Turbine Conference)	*Cranfield University*	*Modelling of Hot Corrosion Resistance for Gas Turbine Materials Systems in Novel Combusted Syngas Environments*	*14th-15th October 2014*	*Brussels, Belgium*	*Scientific Community, Industry*		*Worldwide*
15° Congresso Nazionale Associazione Italiana Prove non Distruttive	*RSE*	*Prove non distruttive innovative nell'ambito dei progetti H2IGCC, SAMBA e Metrosion*	*25 October 2013*	*Trieste Italy*	*Scientific Community (higher education, Research), Industry*	*100+*	*Italy*
Sfide per I materiali nella generazione termica di energia del XXI secolo	*RSE*	*Progetto europeo H2-IGCC: Sottoprogetto materiali: problematiche dei materiali e rivestimenti per turbine a gas alimentate con syngas ad alto tenore di H2*	*12 November 2013*	*Milano (Italy)*	*Scientific Community (higher education, Research), Industry*	*100+*	*Italy*
Presentation at 38th	*RSE*	*solid particle erosion*	*26-31 January*	Daytona	*Scientific*	200+	*Worldwide*

International Conference and Expo on Advanced Ceramics and Composites		*of tbcs: jet tester modeling and erosion forecasts*	*2014*	Beach (USA)	*Community (higher education, Research), Industry*		
8th International Charles Parsons Turbine Conference	*Cranfield University*	*Fireside Issues In Advanced Power Generation Systems*	*5-8 September 2011*	Portsmouth, UK	*Scientific Community (higher education, Research), Industry*	100+	*Worldwide*
41st International Conference on Metallurgical Coatings and Thin Films (ICMCTF)	*Cranfield University*	*Protective Coatings for Gas Turbines*	*28 April – 2 May 2014*	San Diego, USA	*Scientific Community (higher education, Research), Industry*	100+	*Worldwide*
Poster at E2C 2012: European Energy Conference	*FZ Jülich*	*Advanced Thermal Barrier Coating Systems for Future Power Plants*	*17-20 April 2012*	*Maastricht, Netherlands*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*200+*	*Worldwide*
Poster at 2nd International Conference on Materials for Energy EnMatII	*FZ Jülich*	*Influence of Manufacturing Parameters on the Lifetime of APS-TBC Systems*	*12-16 May 2013*	*Karlsruhe, Germany*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*200+*	*Worldwide*
Presentation at Turbine Forum 2012	*FZ Jülich*	*Significance of Manufacturing Parameters for MCrAlY-Bondcoat Oxidation and Thermal Cyclic Lifetime of YSZ TBC*	*23-26 April 2012*	*Nice, France*	*Scientific Community, Industry*	*100+*	*Worldwide*

		systems					
Presentation at 3rd German-Japanese Workshop on Thermal Barrier Coatings	*FZ Jülich*	*TBC Systems with MCrAlY-bondcoats: Effect of Coating Manufacturing on Lifetime and Reproducibility*	*25-27 Juni 2013*	*Münich, Germany*	*Scientific Community, Industry*	*100+*	*EU, Japan*
Presentation at European Corrosion Congress, EUROCORR 2013	*FZ Jülich*	*Effect of Alloying Additions on the Oxidation Behaviour of Ni-base Superalloys in Dry and Wet Gases*	*1-5 September 2013*	*Estoril, Portugal*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*50+*	*Worldwide*
Presentation at Euromat 2013	*Fz Jülich*	*Effect of MCrAlY-bondcoat processing on the lifetime of APS-TBC systems*	*11-13 September 2013*	*Sevijja, Spain*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*500+*	*Worldwide*
Presentation at 41st International Conference on Metallurgical Coatings and Thin Films	*FZ Jülich*	*Effect of Process Parameters on MCrAlY Bondcoat Roughness and Lifetime of APS-TBC systems*	*28 April – 02 May 2014*	*Maastricht*	*Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias*	*200+*	*Worldwide*

Section B (Confidential[8] or public: confidential information to be marked clearly)
Part B1

The applications for patents, trademarks, registered designs, etc. shall be listed according to the template B1 provided hereafter.

The list should, specify at least one unique identifier e.g. European Patent application reference. For patent applications, only if applicable, contributions to standards should be specified. This table is cumulative, which means that it should always show all applications from the beginning until after the end of the project.

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights[9]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)

[8] Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[9] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2
Please complete the table hereafter:

Type of Exploitable Foreground[10]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[11]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
	Ex: New superconductive Nb-Ti alloy			*MRI equipment*	*1. Medical* *2. Industrial inspection*	*2008* *2010*	*A materials patent is planned for 2006*	*Beneficiary X (owner)* *Beneficiary Y, Beneficiary Z, Poss. licensing to equipment manuf. ABC*

In addition to the table, please provide a text to explain the exploitable foreground, in particular:

- Its purpose
- How the foreground might be exploited, when and by whom
- IPR exploitable measures taken or intended
- Further research necessary, if any
- Potential/expected impact (quantify where possible)

19 A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

11 A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

3. Report on societal implications

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*

Grant Agreement Number:	239349
Title of Project:	Low Emission Gas Turbine Technology for Hydrogen-rich
Name and Title of Coordinator:	Christer Björkqvist

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***0Yes 0No***
2. Please indicate whether your project involved any of the following issues (tick box) :	***YES***
RESEARCH ON HUMANS	
• Did the project involve children?	NO
• Did the project involve patients?	NO
• Did the project involve persons not able to give consent?	NO
• Did the project involve adult healthy volunteers?	NO
• Did the project involve Human genetic material?	NO
• Did the project involve Human biological samples?	NO
• Did the project involve Human data collection?	NO
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	NO
• Did the project involve Human Foetal Tissue / Cells?	NO
• Did the project involve Human Embryonic Stem Cells (hESCs)?	NO
• Did the project on human Embryonic Stem Cells involve cells in culture?	NO
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	NO
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	NO
• Did the project involve tracking the location or observation of people?	NO
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	NO
• Were those animals transgenic small laboratory animals?	NO
• Were those animals transgenic farm animals?	NO
• Were those animals cloned farm animals?	NO
• Were those animals non-human primates?	NO

RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	NO
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	NO
DUAL USE	
• Research having direct military use	NO
• Research having the potential for terrorist abuse	NO

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	2	13
Work package leaders	2	14
Experienced researchers (i.e. PhD holders)	9	4
PhD Students	3	7
Other	12	21

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	**12**
Of which, indicate the number of men:	8

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project? ○ Yes / x No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
❑	Design and implement an equal opportunity policy	○	○	○	○	○
❑	Set targets to achieve a gender balance in the workforce	○	○	○	○	○
❑	Organise conferences and workshops on gender	○	○	○	○	○
x	Actions to improve work-life balance	○	○	x	○	○
○	Other:					

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

x No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

○ Yes- please specify

x No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

x Yes- please specify: Website, booklets

○ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

x Main discipline[12]:

○ Associated discipline[12]: ○ Associated discipline[12]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)* x Yes / ○ No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

○ No

○ Yes- in determining what research should be performed

○ Yes - in implementing the research

x Yes, in communicating /disseminating / using the results of the project

[12] Insert number from list below (Frascati Manual).

11c	**In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?**	x ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

- ○ No
- x Yes- in framing the research agenda
- x Yes - in implementing the research agenda
- x Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- X Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid	X	Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	X

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ○ European level
- x International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**14**
To how many of these is open access[13] provided?	**14**
How many of these are published in open access journals?	**9**
How many of these are published in open repositories?	**5**
To how many of these is open access not provided?	**0**
Please check all applicable reasons for not providing open access:	
❑ publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[14]: ……………	
15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**0**

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	
	Registered design	
	Other	x

17. How many spin-off companies were created / are planned as a direct result of the project?	
Indicate the approximate number of additional jobs in these companies:	

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑ Increase in employment, or	❑ In small & medium-sized enterprises
❑ Safeguard employment, or	❑ In large companies
❑ Decrease in employment,	❑ None of the above / not relevant to the project
x Difficult to estimate / not possible to quantify	

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*

[13] Open Access is defined as free of charge access for anyone via Internet.

[14] For instance: classification for security project.

Difficult to estimate / not possible to quantify	x

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

x Yes ○ No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

x Yes ○ No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

x	Press Release	x	Coverage in specialist press
❑	Media briefing	❑	Coverage in general (non-specialist) press
❑	TV coverage / report	❑	Coverage in national press
❑	Radio coverage / report	x	Coverage in international press
x	Brochures /posters / flyers	x	Website for the general public / internet
❑	DVD /Film /Multimedia	x	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

❑	Language of the coordinator	x	English
❑	Other language(s)		

***Question F-10*:** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES
1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]
1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
1.3 Chemical sciences (chemistry, other allied subjects)
1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)
1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY
2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised

technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]