**Programme Area:** Carbon Capture and Storage

**Project:** High Hydrogen

**Title:** Executive Summary


## Abstract:

The High Hydrogen project seeks to identify the safe limits for use of higher levels of hydrogen in the feedstock to combustion plant utilising heat recovery plant and if necessary develop safety standards to support the findings of the project. This project has investigated the risk potential from use of high hydrogen fuels in conventional turbines or engines with exhaust ducting leading to heat recovery equipment. The fuel valves in these systems take seconds to close when the system detect a flame failure or in a fault situation so the volume of gas and any diluents passing into the hot ducting prior to full shut down and purge is of interest. Established laboratory test devices have be used to investigate the effects of differing fuel / diluent compositions in the ducting in terms of the potential for ignition, and the strength of the event. This allows for the definition safe levels of hydrogen in the fuel and avoid the potential for a catastrophic event. The first deliverable from this project comprises of a full literature review of data currently available, a fuel matrix identifying the current fuels containing hydrogen and a test plan to fill in the gaps of current knowledge regarding the energetic reaction of these fuel sources. The findings from these tests will be used to develop the tests planned on industrial scale test plant in the next phase of this project.


## Context:

Hydrogen is likely to be an increasingly important fuel component in the future. This £3.5m project was designed to advance the safe design and operation of gas turbines, reciprocating engines and combined heat and power systems using hydrogen-based fuels. Through new modelling and large-scale experimental work the project sought to identify the bounds of safe design and operation of high efficiency combined cycle gas turbine and combined heat and power systems operating on a range of fuels with high and variable concentrations of hydrogen. The goal of the project was to increase the range of fuels that can be safely used in power and heat generating plant. The project involved the Health and Safety Laboratory, an agency of the Health and Safety Executive, in collaboration with Imperial Consultants, the consulting arm of Imperial College London.

# ETI Executive Summary

**Programme:** Distributed Energy

**Project Name:** High Hydrogen

**Deliverable:** DE1010 / WP1: Literature review of CCGT/CCGE/CHP systems operating on high hydrogen content gases

## Introduction

The objective of the Distributed Energy (DE) Programme is to increase the up-take of DE through the development of integrated systems in order to reduce through-life costs, improve ease of installation and increase efficiency in the combined generation of heat and electricity.

Within this programme framework the High Hydrogen project seeks to identify the safe limits for use of higher levels of hydrogen in the feedstock to combustion plant utilising heat recovery plant and if necessary develop safety standards to support the findings of the project.

In particular this project has been developed to investigate the risk potential from use of high hydrogen fuels in conventional turbines or engines with exhaust ducting leading to heat recovery equipment. The fuel valves in these systems take seconds to close when the system detect a flame failure or in a fault situation so the volume of gas and any diluents passing into the hot ducting prior to full shut down and purge is of interest. Established laboratory test devices will be used to investigate the effects of differing fuel / diluant compositions in the ducting in terms of the potential for ignition, and the strength of the event. This will allow us to define safe levels of hydrogen in the fuel and avoid the potential for a catastrophic event.

The first deliverable from this project comprises of a full literature review of data currently available, a fuel matrix identifying the current fuels containing hydrogen and a test plan to fill in the gaps of current knowledge regarding the energetic reaction of these fuel sources. The findings from these tests will be used to develop the tests planned on industrial scale test plant in the next phase of this project.

## Basis of Report Findings

The summary of the report detailed in this report have been placed in sections as per the actual report. If further detail is required then the relevant report section can be consulted.

## Types of power plant considered

The report covers the main systems currently in commercial use, including combined cycle gas turbines (CCGT) operating with a typical efficiency of 60%. These operate with a typical exhaust temperature range of 300-600℃, some co-firing fuel in the turbine exhaust duct to provide the required temperatures in the heat raising steam generating boiler. Due to the temperature changes it is not uncommon in these systems to have two distinct steam boilers operating at 60-90 bar and 5-10 bar to gain the maximum efficiency. These CCGT plants tend to be large generation units. If the steam cycle is not used or is shut down the system efficiencies fall rapidly to about 37%.

Combined cycle gas engines are generally available in the 0.25 -10MW electrical generation range. Engines can cope with a wider range of fuel types and fuels which are less clean than those required by turbines. Gas engines have efficiencies up to 44%. In the generation areas these are used heavily in Combined Heat and Power systems. They already operate on high hydrogen fuels, however these are de-rated as the hydrogen level increases due to pre ignition in the combustion chamber under compression. The exhaust temperatures and mass flow rates are generally lower than that of turbines and the use of co-fired boilers to generate steam at the designed temperatures and pressures can be used.

These systems when operating on higher level hydrogen fuels must carry out scrubbing of the exhaust gases to reduce the $NO_x$ emissions generated by the higher temperatures of combustion from high hydrogen. Catalytic oxidation is also used to reduce the CO levels within the gas engine plants.

Integrated gasification combined cycle plant are in operation generally operating on coal and these have been developed to provide cleaner greener plant. This type of plant is seen as the option for future power stations due to the potential of using renewable fuel sources and the fact that they are cleaner plants with an option of pre combustion carbon removal.

The reports discusses the options for carbon capture in both pre and post combustion options as well as oxyfuel technologies and the merits / issues with each option.

## Fuel types and sources

Hydrogen is a reactive gas and will react with many other feeds and products, it affects many metals and there can be significant loss of structural strength in a process known as hydrogen embrittlement. Turbines have been operated on 100% hydrogen however the normal level is currently 65-95%, with larger devices having much lower levels at the combustion inlet, however the higher the hydrogen the greater potential for $NO_x$ and nitrogen or steam are introduced to reduce this, these do reduce the actual capacity of the unit, however the mass of these also increase the output of turbines in the expansion part of the turbine.

Syntheses gases are generated by the gasification of coal and generally contain high hydrogen levels but tend to have lower energy concentrations than natural gas, typically 50% lower. These syngases also typically have 25% of the volumetric heating capacity compared to natural gas. However syngases contain higher levels of water vapour and so the heat energy transfers more readily to turbines or engines increases putting thermal strains on the equipment, but also recover greater energy in the turbine due to the increased mass flow rate.

Producer gas is also a syngas and is generated from the gasification or incomplete combustion of biomass or waste products. The composition of these gases varies with the feedstock and treatment, but all contain carbon monoxide, hydrogen, traces of methane or other hydrocarbon. These gases tend can be used on reciprocating engines, although the quality of the fuel is poor. When the gas is cleaned it provides turbine fuel by using a water shift for the carbon monoxide and providing full pre combustion carbon capture at an effective cost.

Refinery gas can contain up to 80-95% hydrogen and are readily available in industry today.

Impurities of higher hydrocarbons, aromatics and tars in these types of fuels will be modelled in computer simulations to determine their effects on the propensity to ignition.

Steam is used in all the fuels systems above to reduce the $NO_x$ levels by reducing the combustion temperature. The addition of nitrogen and steam also add mass flow to the combustion and this offsets some of the derating.

The paper carries out some detailed stoichiometry calculations for the three key gases identified (refinery gas, syngas and producer gas from biomass) and all demonstrate potential for reducing the current fuel inputs of current power stations if these fuels can be utilised.

The study of fuels determined that the air fuel ratios left the content of hydrogen below the lower flammable limit of hydrogen mixed fuels. There is not currently any predictive work available from mixing rules to support the goals of this project, by reliable calculation of ignition characteristics

## The combustion process

There has been extensive research carried out on all these fuels and there constituent parts, however most have been performed either at elevated pressures or with laminar flows. This project is investigating ignition in low pressure, turbulent conditions in turbine and engine ducting. A description of auto ignition, flame development and flame speed are all provided within the report. The report describes the fundamental influence of duct turbulence and duct temperature which both have a significant effect on auto ignition of the gases in the duct during a shutdown from a flame failure event. Hydrogen can actually combust if the turbulence is of a significant level, this is felt could occur in a heat recovery boiler tube bundle area.

The report carries a detailed explanation of deflagration and deflagration to detonation transition, however the areas of most interest was determined as the actual strength generated by the detonation as it was felt the system would detonate and it is important to understand the actual levels that can be designed for regarding plant integrity.

The report determined the areas that are not currently covered by research and these include integrated models for mixed fuels and thus mixed fuels should be tested to determine their reactivity.

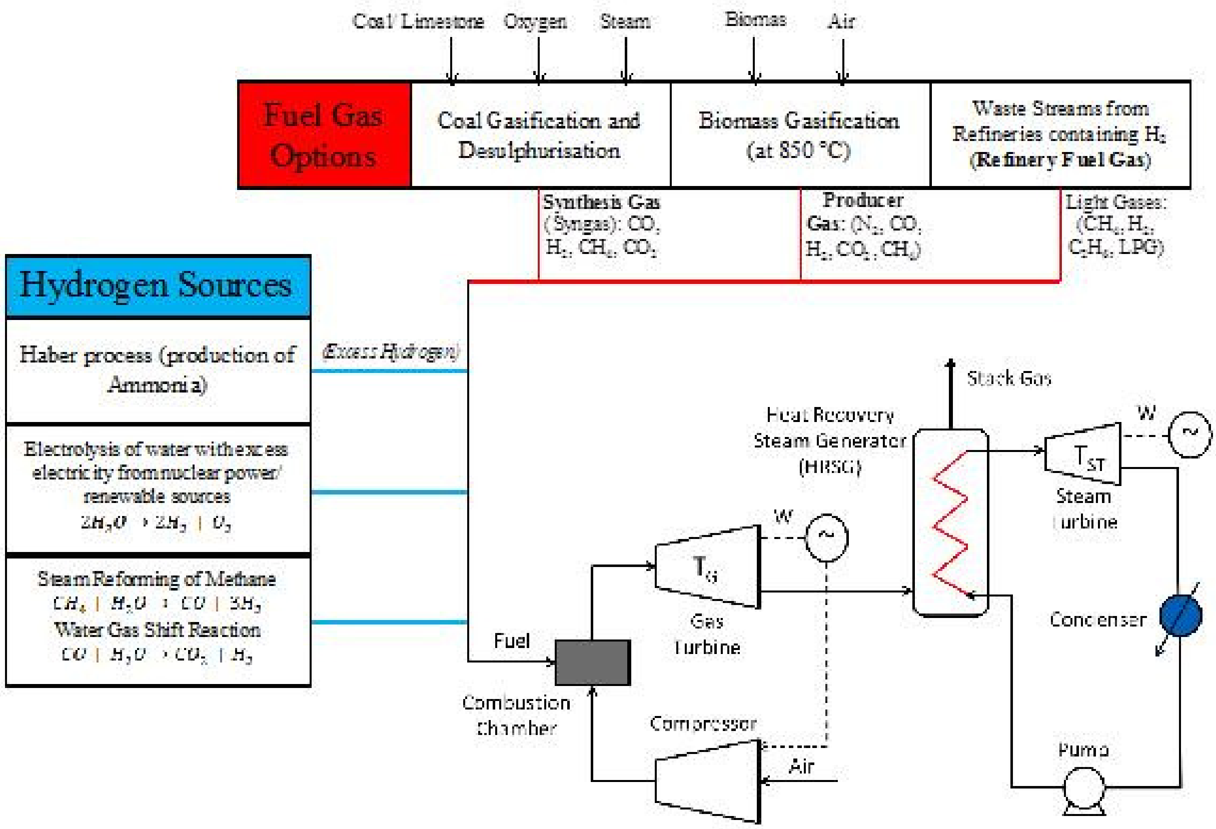


**Figure 1:** Fuel Gas Options and Hydrogen Sources for CCGT Power Generation

## The scaling principles

This section covered the rules being used to scale the demonstrator plants being constructed for trial at The Health and Safety Laboratories. From the original tender a Viper engine was selected to provide the temperature and mass flow rate in the ducts, HRSG to provide real world experience of the fuels selected for testing. It was felt that there were several methods that could be adopted, each of these was used to determine the plant scale fraction, Geometric similarity, Froude number (Buoyancy), Reynolds number (Turbulence) and Heat release rate (Power output). These demonstrated ratios from 1-6.4 to 1-5.2 providing clear scaling options within practical limits.

## Current Industrial practices

There are many examples of combustion plant operating on fuels containing high hydrogen mixes. However there are no examples of these systems being utilised with extensive heat recovery to support improved operational efficiencies. Currently these may be used to generate electricity but not using the most efficient practices. The plant that is operating on these fuels is de-rated to improve the safety of operation and to protect the plant. The OEM manufacturers of turbines have focused on improving efficiency over the last 20 years and a substantial investment has been made on the burner side to open up alternative fuel markets and this has developed the Dry Low $NO_x$ Combustor. Selective catalytic reduction systems have also matured. Currently an uncontrolled burner operating on pure hydrogen can produce up to 400ppm $NO_x$. The study found that if in normal operation a turbine flame failure could provide an 8-12% mixture of hydrogen by volume in the exhaust duct before the slam shut valve had fully closed. This is within the explosive limits for hydrogen. If a flame failure occurred during a start up or ramp up operation then this could elevate to 20%.

Table 1 below demonstrates the key fuel types containing hydrogen and their sources. It can be seen from these and the data provided by the European Turbine Network that the key combustible constituent of these gases are Hydrogen, Carbon Monoxide and Methane mixed with a variance of diluents, Water, Nitrogen and Carbon Dioxide.

| **Fuel stream** | **Fuel reference No.** | **Fuel composition (mol%)** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **$H_2$** | **CO** | **$CH_4$** | **H/C** | **$N_2$** | **$CO_2$** | **$H_2O$** |
| **Hydrogen** | 1 | 100 | | | | | | |
| **Refinery gas (Moliere)** | 2 | 20 | | 50 | 27 | | | |
| **Syngas(Walton)** | 3 | 24 | 67 | | | 1 | 4 | 3 |
| **Producer gas (biomass)** | 4 | 15 | 19 | 3 | | 51 | 12 | |
| **ETN reference fuel** | 5 | 85.8 | 1.2 | | | 8.9 | 4 | 0.04 |
| **GE syngas Fuel** | 6 | 23.8 | 58 | 0.02 | | 8.7 | 0.6 | 8 |
| **Syngas 1** | 7 | 14.5 | 23.6 | 1.6 | | 49 | 5.6 | 5.7 |
| **Syngas 2** | 8 | 34.4 | 35.1 | 0.3 | | | 30.2 | |
| **Syngas 3** | 9 | 61.9 | 26.2 | 6.9 | | 2.2 | 2.8 | |

| Fuel stream | Fuel reference No. | Fuel composition (mol%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $H_2$ | CO | $CH_4$ | H/C | $N_2$ | $CO_2$ | $H_2O$ |
| **Syngas + CCS** | 10 | 47 | 1 | 1 | | 41 | | 10 |
| **COG** | 11 | 61.6 | 6 | 23 | 2.2 | 5.4 | 1.2 | |
| **Refinery Gas** | 12 | 28 | | 28 | 34 | 3.5 | 6.5 | |
| **Bio Syngas** | 13 | 18 | 20 | 7 | 2 | 30 | 23 | |

Table 1 constituent components for fuels currently available.

Initially from this study the consortium selected the gases detailed in table 2 below. However the technical advisory committee discussed alternatives to this and it was agreed to use a sliding scale of mixtures to build up greater knowledge on the reactions involving mixed fuels. During these tests the consortium will identify approximately which gas the mixture represents. The diluents are only going to be modelled with computer programs. In the future it would be an option to carry out the same tests on mixtures including alternatives to Methane.

| Fuel stream | Fuel reference No. | Fuel composition (mol%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $H_2$ | CO | $CH_4$ | H/C | $N_2$ | $CO_2$ | $H_2O$ |
| **Hydrogen** | 1 | 100 | | | | | | |
| **Syngas 1** | 7 | 14.5 | 23.6 | 1.6 | | 49 | 5.6 | 5.7 |
| **Syngas + CCS** | 10 | 47 | 1 | 1 | | 41 | | 10 |
| **COG** | 11 | 61.6 | 6 | 23 | 2.2 | 5.4 | 1.2 | |

Table 2 Initial gas selection

The Viper engine exhausts was calculated on the basis of firing butane gas in place of the standard kerosene to support the scaling factors required by the next work phases on the circular duct and the HRSG. At 100% load the unit requires a fuel flow of 0.4kg/s and at 92% 0.284kg/s. This is approximately 9% less than when in operation on kerosene.

In the plants recovering heat from the turbine or engine units there can be duct firing to improve efficiencies and to enable the units operation when the prime mover is not operational. These HRSG systems are today tending to be multiple pressure units in a drive for greater efficiency from the power stations. The literature review provides an in-depth investigation into the horizontal and vertical design advantages and disadvantages for efficiency and operation. It tends to vary which of these arraignments is most efficient based on the size of the unit and the pressure temperature outputs.

Control systems for dealing with combustion of fuels of changing quality, covering natural gas and LNG. These include wide Wobbe systems, based on a computer algorithm. These have a reaction time of approximately 50ms and can control effectively to a 20% change in Wobbe Index values. Hydrogen has been found to provide a stable flame with diffusion combustion system and hence there is less concern regarding Wobbe Index for pure hydrogen. Optical flame detectors are also used in gas turbines, however these are prone to contamination that gives a false result.

For the turbine and engine market there appears to be a reasonable level of experience for high hydrogen fuels, however these controls all focus on the turbine or engine operation and there has been little thought regarding the ducts and heat exchangers. The control systems all appear to cope well with these plants for the combustion plant, but again do not apply the safety to the plant after the combustion process.

## Incidents

This section of the report has a restriction on publication, but can be shared with members on request.

The HSE records were evaluated for incidents reported between 1981 to 2004. 343 relevant incidents were reported, 7 related to explosions in the exhaust systems all in off shore applications, 554 turbines were in operation during the period under investigation, this data provided an estimated risk ratio of 1 in 1400 per year. The main cause of these incidents occurred during start up, over fuelling or at fuel change over in operation. Since 2004 the recoding process and the types of plant in operation have changed making it difficult to directly interpret the data. There is evidence from RIDOR records and Corporate Operational Information databases that there were five fires and six explosions in the exhaust systems of turbines or engines in operation. One of these reported that the residual heat in the Selective Catalytic Reduction system had ignited the excess fuel in the system.

## Regulatory regimes

The study includes EU and USA standards and regulations, although they are applied differently in the two regions it was felt that this approach provided the best quality information. The report includes all the standards with guidance notes defining their applicability. The study investigates safe handling and storage of hydrogen, explosion prevention and protection, as well as safe design and operation of CCGT/CCGE/ and HRSG systems. These are well defined and the selected sections that apply to hydrogen fuels used for these applications.

## Conclusions

The hazard regimes for operating CCGT and CCGE power generation systems with enhanced or high hydrogen fuels have been identified. Assuming equivalent reactant / air ratios near “1”:

- If at the temperature regimes of interest the system can be kept or brought outside the flammability regime, e.g. by supplementary air through by-pass or directly in to the exhaust duct, then there are no hazards for ignition of non-combusted fuel. Favourable conditions for this can be created by adequate mixture dilution, although this is only true for some failure scenarios.
- If in thorough testing under the above conditions of mixtures within the fuel flammability regime, no spontaneous or artificial turbulence/kernel formation can be detected, then the system will be safe, as long as over-pressures from deflagrations can be safely contained. Favourable conditions for this can be created by mixture dilution, duct design and rapid remedial action.
- If turbulence or flame kernel generation can be detected then the potential for artificial or spontaneous DDT is present along with the generation of very high over-pressures from stable or quasi detonations. In that case even a perfectly designed exhaust system provides no adequate protection as DDT may be generated within the entry zone of the HRGS. Favourable conditions can only be created by rapid remedial action.
- The assessment of current knowledge, which covers a wide range of characteristic behaviours and explosion hazards of gas mixtures used for CHP generation. Currently available literature gives no specific quantitative information. This is a gap.
- In the document there have been repeated and extensive references on the likely behaviour of gaseous systems in exhaust ducts and HRSG systems of power plants, and highlighted the likely areas for specific hazards such as turbine exhausts, duct corners and HRSG entrance, including and specifically within the heat exchangers.
- Current CCGT systems when operating on high hydrogen fuels may, following a flameout, result in hydrogen concentrations exceeding the LFL entering the exhaust system.
- No Standards or Codes of Practice were found that apply specifically to CCGT/CCGE/CHP systems operating on high hydrogen fuels.
- Several existing Standards and Codes of Practice have relevant sections that should be applied when considering high hydrogen fuels.
- Where there is a foreseeable risk of a flammable mixture entering the exhaust system and the HRSG, then the ATEX regulations (EU only) should be complied with in order to mitigate the risk of an explosion.
- The particular areas where knowledge is insufficient or non-existent or impossible to realise (further gaps) in the context of the current hydrogen rich fuel streams are:
    - Qualitative information relating to possible outcomes following ignition.
    - Quantitative information relating to the understanding of actual outcomes following ignition.
    - Mixing rules for extrapolation and/or interpolation of results.
    - Probability of ignition related to mixture strength in a turbulent flow field.
    - Probability of DDT related to mixture strength following ignition.
    - Scaling behaviour suitable for estimation of extrapolation and/or interpolation of results.

## Selected gas test matrix

The technical advisory committee (E.ON, Rolls Royce, and Caterpillar) and the consortium agreed upon a change to the selected three fuels detailed in the report for testing. It was felt that this actually provides data relevant for the whole fuel range provided by the report. A hydrogen, methane blend and a hydrogen carbon monoxide blend of fuels is to be tested to determine any limits for practical operation.

## Recommendations

The test matrix for WP2.1, Task 1 is discussed and approved.

The revised situation regarding the detonation work is discussed and resolved as the technical support team have instructed that this is of a much lower importance as they believe if the fuels are mishandled there will be an ignition and the strength of this is more important so the fuel blend limits are of greater importance, so a safe limit can be identified.

The option for external purchase for ADT data is discussed and a decision made on whether to proceed with purchasing it from a Chinese or UK source.

The possibility, following a flameout, that any unburnt fuel may burn off as it goes through the hot turbine is investigated, particularly for the high hydrogen fuels of interest.

The potential application of the ATEX directive to CCGT/CCGE systems is discussed further with the UK regulator.