NATURALHY

Preparing for the Hydrogen Economy by Using the Existing Natural Gas System as a Catalyst

Project Contract No.: SES6/CT/2004/502661

Using the Existing Natural Gas System for Hydrogen

SIXTH FRAMEWORK PROGRAMME

www.naturalhy.net

Welder inside Two Sections of 48" Pipe,
Welding the Seam to Create One Continous Section of Pipe

Published October 2009

SIXTH FRAMEWORK PROGRAMME

table of contents

1

Executive Summary

The European Commission-supported NATURALHY project was set up to investigate whether hydrogen could be delivered safely via the existing European natural gas network. This has involved mapping out the feasibility, the consequences and the benefits of using the natural gas network for the safe and efficient transport of mixtures of hydrogen and natural gas across Europe. As such, the project has demonstrated the capabilities of the natural gas network for hydrogen delivery, which can be, potentially a major contribution towards sustainability.

Hydrogen is expected to become an important future energy carrier because it can significantly improve the security of energy supply and reduce/avoid emissions of greenhouse gases. A range of sustainable sources, including biomass, can be used for the production of hydrogen. It can be produced from the gasification of coal, with or without Carbon Capture and Storage (CCS) and is also a by-product in many chemical processes. Of course, the combustion of natural gas with added hydrogen emits less carbon dioxide per energy unit than the combustion of pure natural gas, as the combustion of hydrogen is "carbon free".

The objective of the NATURALHY project has been to define the conditions under which hydrogen could be added to the natural gas transport network without unacceptable impact on the integrity of the network, safety, and the performance of natural gas appliances. The project has proved that:

- depending on the steel from which high pressure pipelines are constructed, these pipelines could be used for gas mixtures that contain up to 50% of hydrogen

- safety related to the transmission, distribution and use of natural gas is not significantly compromised compared to the current situation with natural gas if up to 20% of hydrogen is added to natural gas. Additions up to 50% might be feasible but must be assessed case by case

- the maximum percentage of hydrogen that can be allowed to ensure proper end-use performance depends on appliance type and condition as well as on local natural gas distribution conditions. For domestic appliances, a method has been derived to address these questions on the level of a distribution region (country)

There is no doubt that the NATURALHY project has been an important step in providing hitherto unavailable information which could make a significant contribution to the 'greening' and de-carbonisation of natural gas with hydrogen.

However, there are two very important points to note:

- there are no simple answers.

Each potential addition of hydrogen to a particular part of the European gas network must be considered individually in conjunction with the project's Decision Support Tool; (see chapter 10)

- there are some aspects of the gas network that have not been investigated in full detail, as they were beyond the scope of the NATURALHY project.

2

Introduction

It is important to begin by stating that the use of hydrogen can be regarded as controversial and, contrary to much popular belief, it is not the new wonder source of energy that will solve all of our energy problems; it is simply an energy carrier, its method of production being of critical importance in determining its contribution to sustainability. Nevertheless, there is considerable interest in the 'Hydrogen Economy' which means that some way must be found for moving hydrogen around between sources and points of use in Europe. If we want to avoid clogging up the roads with hydrogen tankers, an alternative means of shipping hydrogen safely and economically has to be found. An obvious option was to consider using the existing European natural gas system to transport natural gas/hydrogen mixtures and, with a few labour pains, the NATURALHY project was born. The basic vision is that the mixture of hydrogen/natural gas should be suitable for use as such. In addition, the option of separating hydrogen from the mixture by means of membrane filters has been investigated. Both these possibilities are interesting options for de-carbonising current energy systems.

This brochure presents the results obtained in this ground-breaking research project which has been designed to identify the potential of the existing European natural gas network for the safe delivery of hydrogen. The NATURALHY project is a unique, international research effort, which has been supported throughout by the European Commission's Sixth Research and Development Framework Programme, FP6.

Results are presented here, in summary form, for those interested in energy and its transition towards a more sustainable energy future. Our intention is to raise awareness of the issues related to adding hydrogen to natural gas, to highlight the

possible consequences, and to give both evidence and a flavour of what might be realistically achievable. In particular, the results are directed at decision makers at the political level, industry professionals, including those from network companies, researchers in the field of hydrogen and sustainable energy and interested members of the public.

The NATURALHY project has investigated how and to what extent natural gas networks could further support the introduction of hydrogen. The following chapters summarise the consequences of adding hydrogen to natural gas, for the whole delivery chain, from hydrogen injection point in the high pressure transmission grid up to and including end user appliances. Crucially, assessment of the overall environmental and socio-economic benefits of the NATURALHY approach has been an integral part of the project. However, benefits can only be realised if options are technically feasible. Hence, the project has focussed on potential "show stoppers", so that only the most important issues have been investigated, leaving out subsequent considerations which are expected to be solvable, although sometimes with substantial costs. It is very important to note that the research and development of sources of hydrogen was outside the scope of this project.

First, a few facts about **the NATURALHY project**; It started on 1st May 2004, and was completed on 31st October 2009. The project comprised 39 partners, listed in the last chapter in this brochure. The project management team consisted of the Universities of Loughborough and Oxford, GDF SUEZ (formerly Gaz de France), Instituto de Soldadura e Qualidade (ISQ), DBI Gas- und Umwelttechnik, EXERGIA Energy and Environment Consultants S.A., and EUROGAS – GERG (The European Gas Research Group).

The project was coordinated by N.V. Nederlandse Gasunie. The project budget amounted to €17 million, including a European Commission grant for € 11 million. Further information is available on the project website **www.naturalhy.net**

3 Background: the role of hydrogen in the transition towards a sustainable energy society

Important energy issues that the world is facing now concern the security of supply and polluting emissions, particularly greenhouse gases. The current transition towards more sustainable energy sources aims to deal with these issues. The transitional changes being implemented involve both technical and non-technical aspects, including, for instance, developing new energy carriers and applications and reducing energy demand. For the following three reasons an important role is foreseen for hydrogen as an energy carrier in a sustainable energy society:

1. Hydrogen can be produced in many ways from locally available energy sources including electrolysis of water using electricity produced from wind or solar energy, or from gasification of biomass. Using such sustainable energy sources for hydrogen production can improve security of energy supply.

2. The levels of pollution from controlled hydrogen combustion are relatively low and, if produced from sources with low emissions, hydrogen is a relatively clean fuel. Mobile applications fuelled with pure hydrogen can improve local air quality by replacing petrol and diesel in cars and buses.

3. As pure hydrogen can be converted by fuel cells into electricity and vice-versa with high efficiency, it has potential for storage of electrical energy (such as in the case of electricity generation from wind energy when supply exceeds demand).

Although research activities on crucial topics such as the sustainable production of hydrogen, hydrogen storage, and fuel cells are still on going, it is broadly expected that hydrogen will be an energy carrier of increasing importance in our energy mix. This expectation is based on the conclusion that in the near future, say after 2015, significant volumes of hydrogen can be produced from the gasification of coal or biomass: the gasification of biomass is almost "carbon-neutral" and with carbon capture and storage (CCS), carbon dioxide emissions related to coal gasification can be relatively low. Potential supplies of biomass are substantial and global coal reserves are immense. Reduction of carbon dioxide emissions by replacement of fossil fuels with hydrogen produced from "low carbon" sources of energy could contribute to de-carbonisation and 'greening' of our energy economy.

4

The NATURALHY approach: what can the natural gas system offer for the delivery of hydrogen?

The first logical step towards a transitional delivery system suitable for hydrogen and hydrogen-containing gases must be an investigation of the extent to which existing assets, including the existing natural gas pipeline infrastructure, can be used for hydrogen delivery.

In principle, the existing European natural gas system offers the following opportunities:

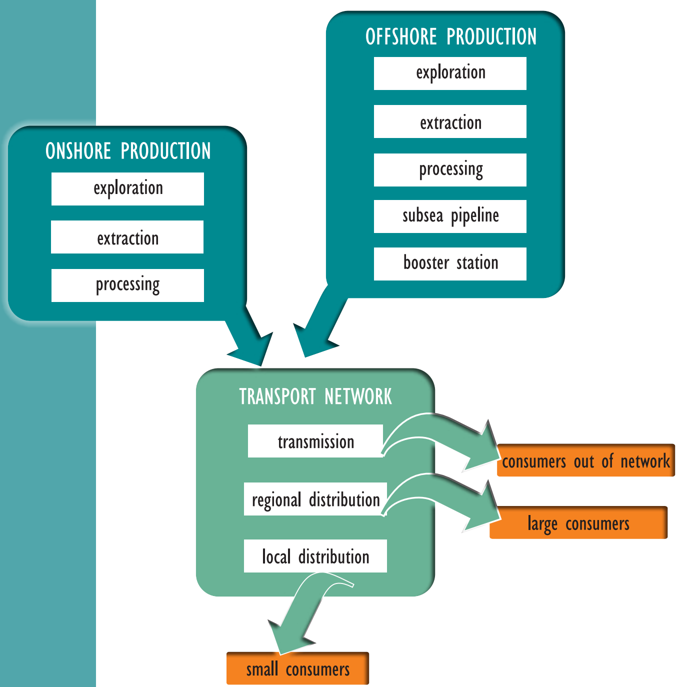
- in place, so potentially cost-effective and available in the short term
- well-established grid management and operation strategies
- widely spread and interconnected
- very high capacity
- well-established safety procedures and an excellent safety record, based on a well-developed maintenance and control structure
- broad acceptance by the public.

Generally speaking, a network designed for natural gas cannot be used for pure hydrogen for a number of reasons, without modifications to network components or the way it is operated and maintained. The point is that the physical and chemical properties of hydrogen differ significantly from those of natural gas. The differences concern, amongst other considerations, density, calorific value, ignition energy, flammable limits and burning velocity. Even the addition of a certain percentage of hydrogen to natural gas will have a direct impact on;

- combustion properties
- diffusion into materials and effect on their mechanical properties
- behaviour of the gas mixture in air.

As a result of these contrasting properties, a system designed for natural gas cannot be used without appropriate modifications for pure hydrogen, and vice-versa.

However, the existing natural gas transmission, distribution and end-use systems could be used, with suitable adjustments, for mixtures of natural gas and hydrogen. In this case, the hydrogen/natural gas mixture can be used directly or, if required, hydrogen appliances could be fuelled with "pure" hydrogen by developing devices to extract hydrogen selectively from the



Summary of the Existing Natural Gas System

mixture. The definition of the conditions under which hydrogen can be added without unacceptable consequences to natural gas, and the development of devices for hydrogen separation from a mixture, has been an important part of the NATURALHY project.

In principle, hydrogen can be added to natural gas in the high-pressure grid, in the medium pressure grid, or in the low pressure distribution grid, but it must be remembered that the existing system was designed and constructed specifically for natural gas and, as explained above, the physical and chemical properties of hydrogen differ significantly from those of natural gas. In particular, the addition of hydrogen to natural gas may have an impact on numerous aspects of the existing system. The work done in the framework of the NATURALHY-project to quantify this impact further is described in detail in the following chapters:

- safety related to the transmission, distribution and use of gas
- integrity of pipelines
- gas quality management
- performance of end user appliances
- energy capacity of the delivery system
- gaseous (and energy) losses.

5

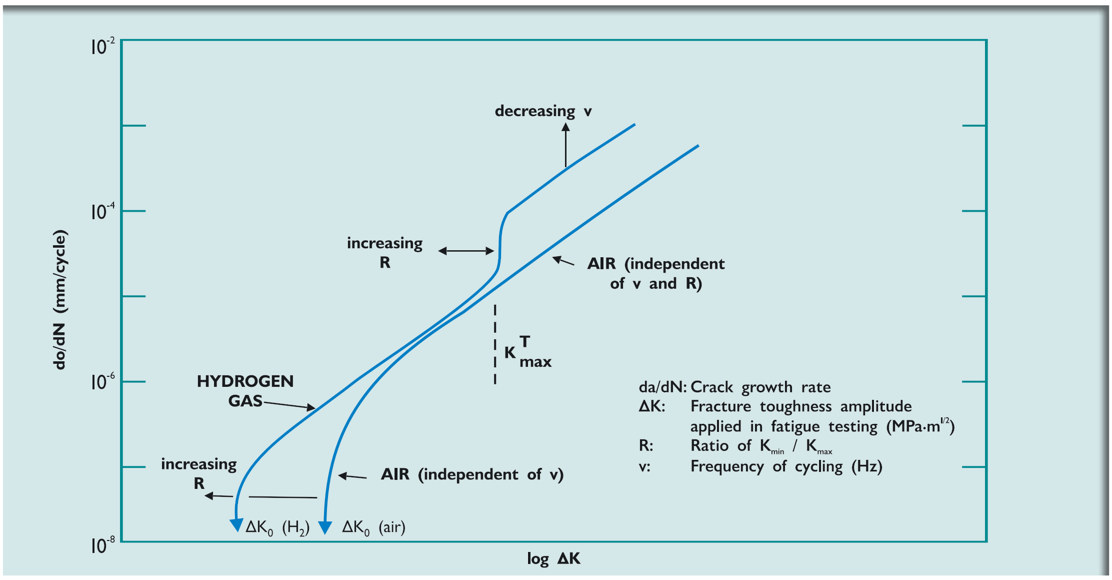
What is the impact of adding hydrogen to natural gas on the durability of the network?

Gas transportation and distribution networks are very complex and inhomogeneous infrastructures. Adding hydrogen to natural gas will lead to direct contact of gaseous hydrogen with the networks and the associated installations that have been designed specifically for natural gas.

The influence of hydrogen on the different materials is diverse. Steel materials can change their material properties in the presence of hydrogen if there is direct contact of hydrogen with clean metal surfaces. In this case, the fatigue properties and toughness of steels, used for the gas transportation pipelines, are influenced in a detrimental way. This material degradation results in higher crack growth rates and can lead to the initiation of new cracks. Consequently, the service life of pipelines can be decreased in comparison to service with natural gas. Furthermore, the pipeline integrity management strategy needs to be adapted as the systems in use focus on corrosion defects and not on cracks or crack-like defects. On the positive side, the risk of fast, long-distance crack propagation in the pipeline is reduced, as hydrogen addition will have a beneficial effect, due to the more rapid decompression behaviour compared with natural gas. Therefore, propagating ruptures will be stopped more easily and rapidly.

Effect of gaseous hydrogen on resistance of pipe steel to crack growth in fatigue loading

At the downstream end of the gas grids,

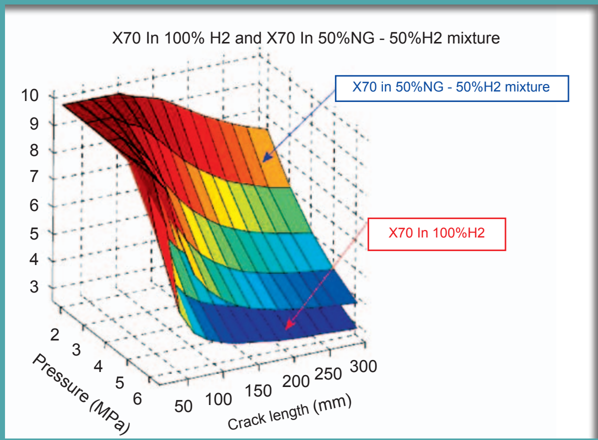


distribution networks are in place to supply natural gas safely and reliably to the end user. Since the late 1980's polymers have been heavily used for the construction of distribution networks because of their beneficial properties for the purpose of low pressure gas distribution. Polymer pipes do not suffer from conventional corrosion even though they undergo degradation over their lifetime. Beyond this they have a much better performance concerning the gas tightness of the connections in comparison to older materials such as cast iron. On the other hand they are less gas tight regarding the loss of gases through their pipe wall (permeation) driven by the concentration gradient.

The amount of natural gas, which cannot be delivered to the customer because of permeation losses is very small and accepted from a safety, economic and environmental point of view. Adding hydrogen to the natural gas will lead to a change in gas losses through permeation, as the transport of hydrogen through the wall of polymer pipes (from inside the pipe to the environment) is quicker than for natural gas. This applies to polyethylene (PE) and also to polyvinyl chloride (PVC). Within the framework of the project various investigations have been performed in order to determine the permeation properties and the corresponding effect on the gas losses. The change in permeation losses has been evaluated from a safety perspective. Apart from permeation, ageing effects have been investigated in order to ensure that adding hydrogen to the distribution network will not affect the lifetime of this infrastructure in a significant way.

The results show that effects on pipe materials used in the natural gas grids, caused by hydrogen, can be mitigated by appropriate measures. Modifications to maintain a safe and reliable supply of customers with natural gas / hydrogen mixtures will mainly be necessary for pipelines made of steel, but importantly, no "show-stoppers" have been identified.

IFP test bench (2 permeation cells)

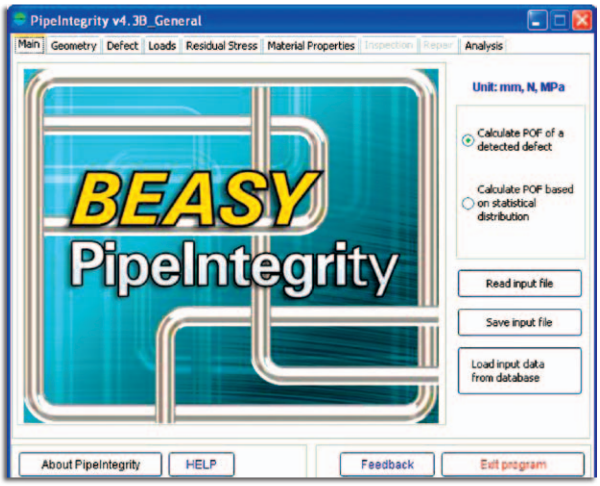


Critical initial axial crack depths for 50% and 100% natural mixtures (required lifespan: 60 years; pipeline steel: X70; Environment: 100% hydrogen; no residual stresses)

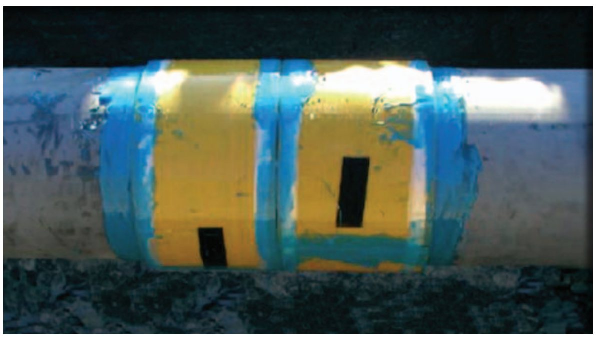
DBI test bench with controlled space and casing according to EG 97/23

6

What measures should be taken to control and monitor the condition of the network?



Pipeline Integrity Assessment Tool


Clock Spring repair of a steel pipeline

The material investigations identified that additional measures will be required to ensure the integrity of steel pipelines, when hydrogen is transported by the existing natural gas system. Consequently the pipeline integrity management systems (PIMS) in place need to be adapted. Modifications will be necessary for wide parts of the existing PIMS as defects, that are currently not in the focus, need to be considered, when hydrogen is transported. Furthermore the extent of the modifications will depend on the hydrogen concentration in the natural gas.

The critical defects regarding the hydrogen transportation are sharp defects (cracks and crack-like defects), as they introduce a significant stress into the pipeline and can lead to interactions between hydrogen and the pipeline material. As well as the defect type, it is very important to know the critical size of defects. Cracks can grow over time (cracks are time dependent defects) so knowledge of the crack growth rate in a certain timeframe can provide the critical initial defect size by back calculation, assuming a particular design life. The critical initial defect size should not be exceeded at the beginning of the period under review. The critical size of cracks and crack-like defects provides important information for the specification of pipeline inspection tools, which need to detect and identify the defects, (when they have achieved a critical size), with a high reliability.

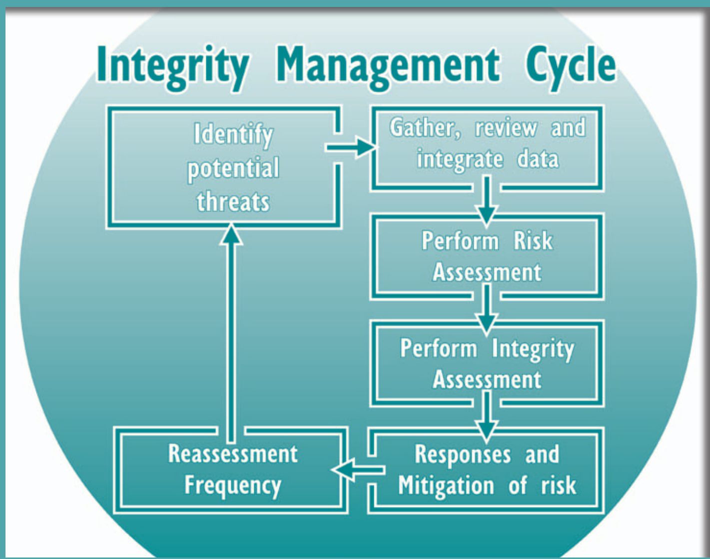
Within the NATURALHY project, critical defect sizes for typical cases were investigated in sensitivity studies. Furthermore, a tool able to calculate the probability that a pipeline or a defect (crack and corrosion) will fail or lead to failure was developed. Based on the results of the sensitivity studies and the Probablility Of Failure (POF) calculations, requirements for in-line inspection tools were summarised. In a large scale test adapted tools were examined to prove whether they met the more stringent requirements. The

[1] Magnetic Flux Leakage (MFL)
[2] TRIAX sensors are used in the MagneScanTM tool (able to detect corrosion and long axial defects)
[3] Electro Magnetic Acoustic Transducer (EMAT)

results suggested that modified inspection tools such as MFL[1], TRIAX[2] and EMAT[3] can be applied in order to inspect gas pipelines containing natural gas / hydrogen mixtures and find critical defects. By using in-line inspection and POF calculation results, the intervals for pipeline inspection activities can be determined for different hydrogen concentrations, loads and geometries of pipelines and defects. It is expected that inspection intervals will be shortened in comparison to the natural gas service, especially for higher hydrogen concentrations. As a countermeasure the improvement of inspection tool performance can offer mitigation, as early detection and reliable sizing of defects is beneficial for lowering the probability of failure.

After having identified defects, an optimisation process of actions has been proposed in order to reduce the costs but still meet the required safety levels. Calculations of net present value have shown that, depending on the amount and distribution of defects, the costs for repair and renewal can be reduced significantly by grouping activities together.

Concerning pipeline repair methods, three currently applied procedures have been investigated regarding their suitability for hydrogen service. The work focused on the abililty of the repair measure to take on the pipeline load and on the effect of hydrogen on welding activities. The investigated repair methods ("Clock Spring", "Metallic Sleeve" and "Weld Deposit") were found to be suitable for repairing hydrogen-containing pipelines even though performance was slightly reduced in some cases.



General flow chart of the integrity management cycle
(source: Report "Integrity Management and the Naturalhy Project")

Finally the effect of adding hydrogen on the costs of integrity management has been investigated. The costs are strongly dependent on individual circumstances, especially regarding hydrogen concentration, defect distribution, material properties, loads and integrity targets. An example was elaborated using material data on defect distributions which reflect pipes in a "medium condition", with a maximum operation pressure of 66 bars and meeting a POF integrity target for corrosion and for cracks after 50 years of operation which is in line with current failure statistics for European natural gas transmission pipelines. With the example considered, it was concluded that, for high concentrations of hydrogen (50%) in natural gas pipelines, there were slight effects on the inspection and repair frequency and therefore increased total costs (inspection and repair for corrosion and cracks) in the order of less than 10%.

Summarising the results overall, it can be stated that, based on the relevant data, appropriate and affordable pipeline integrity management can be put in place for the transportation of natural gas and hydrogen mixtures up to a hydrogen concentration of 50%.

7

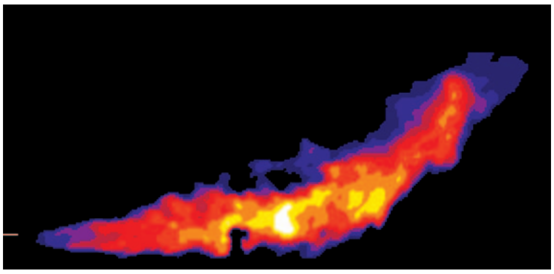
What is the impact of adding hydrogen to natural gas on the safety aspects?

The existing gas pipeline networks are designed, constructed and operated based on the premise that natural gas is the material to be conveyed. The safety of the pipeline system and the risk posed to the public by the supply and use of natural gas are well understood, and considered acceptable, after many years of operational experience and much research into the effects of accidental escapes.

However, hydrogen has different chemical and physical properties which may adversely affect (increase) the risk presented to the public. Risk is a combination of likelihood of an untoward event (such as failure frequency of pipelines or ignition probability) and the consequence (hazard) of the event (such as the severity of a fire or explosion). Adding hydrogen to the gas infrastructure may affect both the likelihood and severity of untoward events and hence potentially increase the risk to the public. The NATURALHY project has focussed effort on quantifying this effect in order to establish if the risk remains acceptable and to identify the maximum hydrogen concentration that can be added to the natural gas without this risk becoming unacceptably high.

To re-assess the severity of the hazard presented by accidental releases of natural gas/ hydrogen mixtures, NATURALHY has studied experimentally, at large scale, the behaviour of gas escapes and explosions in both a domestic and industrial setting and assessed the effect of increasing levels of hydrogen addition. These studies established that escapes of natural gas/ hydrogen mixtures within buildings behave in a similar way to natural gas, in terms of the nature of the accumulation produced. However, the gas concentration and volume of the accumulation increases as hydrogen is added but these increases are slight for hydrogen addition up to 50% by volume. In the event of ignition of a gas escape within a building, the explosion presents a hazard to the occupants. Here, the work of the NATURALHY project has shown that the severity of explosions in buildings increases if hydrogen is added to natural gas. However, the increase is only slight for hydrogen addition of 20%.

Working on the test rig



Thermal image of flame

The closest contact that the general public has with the gas supply system is in their homes, as customers, using the gas for heating and cooking. It is impossible to prevent all gas escapes and currently, a small number of explosions occur each year as a result of gas escapes in domestic properties. Hence, the frequency of such explosions has been re-assessed for natural gas/ hydrogen mixtures. This analysis has suggested that the explosion frequency could increase by up to a factor of 2 as a result of adding 20% by volume hydrogen to natural gas. However, the current risk is very low and even with this increase the risk remains within generally acceptable limits.

From the point of view of the pipeline operator, the main concern is the assessment of the risk that their operations present to the public at large, from the pipeline network and from their gas processing sites, including compressor or pressure reduction stations. Hence, operators need a methodology which will enable them to assess these risks following the addition of hydrogen to the pipeline network. The principal hazard posed by the failure of transmission pipelines is that of a large fire. Hence, NATURALHY has re-assessed this hazard for natural gas/hydrogen mixtures by conducting large scale experiments and developing a mathematical model to evaluate the fire hazard. Using information obtained within the NATURALHY project of the effect of hydrogen on pipeline materials, the failure frequency of transmission pipelines conveying natural gas/hydrogen mixtures was re-assessed, and it was concluded that, with appropriate integrity management of the fatigue life, the failure frequency of transmission pipelines would not be adversely affected to any great extent.

VCE Test Rig

By combining the work on failure frequency, ignition probability and the assessment of fire hazard, NATURALHY has developed an easy to use screening tool (LURAP[4]) which will enable operators to assess the risk posed by the transmission of natural gas/hydrogen mixtures and compare it with current risk levels. LURAP determines, the risk posed by an individual pipeline to a person close by, or an entire network of pipelines to the population as a whole. The results from LURAP suggest that the addition of hydrogen increases the risk to an individual at locations near the pipeline but decreases the risk at locations further away (as the extent of the hazardous region is reduced).

Finally, pipeline operators also need to assess the background level of leakage from their pipeline networks as part of their integrity management and environmental assessments, since methane is a greenhouse gas. A study of the expected background level of 'leakage' from the gas system (through minor defects in the pipelines or by permeation through the pipeline material) has shown that the level of leakage overall is very small and poses no hazard from a safety point of view. Indeed, the addition of hydrogen results in a slight decrease in the level of methane emissions to the atmosphere from the gas infrastructure, which is beneficial from an environmental perspective.

[4] LURAP: Loughborough University Risk Assessment of Pipelines. Available within the DST

8

What is the impact of adding hydrogen to natural gas on end user aspects?

With increasing hydrogen addition to the natural gas supply, the physical characteristics and basic combustion properties of the fuel will be modified, which, in turn, could alter the operation, reliability and safety of appliances. For domestic appliances, personal health and home safety are at stake and tens of millions of appliances in any given country are involved. Furthermore, important data on appliances (types, years in use, maintenance record etc.) in use in each house is quite limited. Thus, while all major classes of end-use equipment have been considered in the NATURALHY project, particular attention has been paid to domestic appliances.

Current fundamental understanding of combustion processes opens the way to analyse the consequences of introducing new distribution gases like natural gas/hydrogen mixtures by performing a limited number of basic combustion calculations and experiments instead of large numbers of appliance tests. This fundamental analysis can be performed for the gas compositions relevant to any national situation, in a straightforward and quantitative way[5]. Consequently, it has been possible to consider the "essential" consequences of hydrogen addition i.e., those causing safety and reliability issues (such as light-back in domestic appliances, overheating of industrial burners, engine knock in gas engines etc.), fitness-for-purpose (thermal input to, and efficiency of, combustion equipment) and environmental issues (such as consequences for emissions of nitrogen oxides). One practical aspect that has not been considered is the life-long physical integrity of gas utilization equipment since all current end-use equipment has been designed, tested and approved for natural gas and not mixtures containing hydrogen.

[5] Method developed by Gasunie Engineering & Technology, Groningen, The Netherlands

There is one effect of hydrogen addition on the performance of combustion equipment that must be emphasised. Taking a given natural gas and "simply" adding hydrogen to it will decrease the Wobbe index of the gas, up to hydrogen fractions in excess of 80%. Since the thermal input (power) to gas utilization equipment is directly proportional to the Wobbe index, the thermal input will decrease in all combustion equipment, except those with power controls (such as power generation equipment).

It is anticipated that, for the time being, natural gas distribution will continue within the existing distribution bands, as defined by a range of Wobbe index values. In the context of the effect of hydrogen addition on the Wobbe index, this fact itself constrains the maximum allowable hydrogen fraction: the Wobbe index of a given natural gas/hydrogen mixture must remain above that of the lower Wobbe limit of the existing band.

From this work, the following conclusions were drawn:

- the maximum hydrogen concentration for the domestic market in a country is determined by the safe operation of properly adjusted conventional domestic appliances as well as by the local conditions of natural gas quality (range and current value of Wobbe Index)

- for properly adjusted appliances and favourable conditions of natural gas quality, conventional domestic appliances can accommodate up to 20% of hydrogen

- for poorly adjusted appliances and/or unfavourable conditions of natural gas quality, no hydrogen admixture is allowed

- stationary gas engines and gas turbines need readjustment and/or modification

- feedstock processing and industrial combustion applications require case-to-case consideration.

Concept for a hydrogen household fuel cells. AA (R6) battery with large compartment filled with bubbling water

Blue flames from gas stove burner. Closeup shot of blue flames from a kitchen gas range

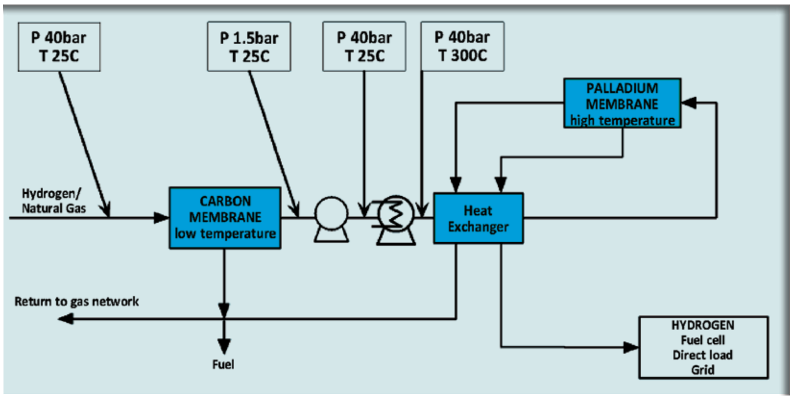
9

Separation of hydrogen from a hydrogen/ natural gas mixture, and its impact on the quality of the remaining gas

The use of the existing natural gas network to distribute hydrogen provides the opportunity to create local “hydrogen centres” by developing separation technologies to provide hydrogen for end users. Separation of hydrogen is a mature technology and in refineries, is usually carried out by pressure swing adsorption (PSA) technology. However, these tend to require large scale units which work best with high levels (greater than 50%) of hydrogen in the feed gas. There is a requirement for smaller scale separation of hydrogen, and when the mixture contains lower levels of hydrogen in the feed gas under typical natural gas pipeline conditions. Hydrogen quality is an important issue for end-use and hydrogen purity needs to be matched to the specific application.

The NATURALHY project has focussed on developing advanced hydrogen-selective membranes for the separation of hydrogen from natural gas/hydrogen mixtures. Membranes are essentially selective molecular filters and operate under a partial pressure driving force, so that the higher the partial pressure difference and the concentration gradient of hydrogen, the more efficient the separation. The focus has been on:

- laboratory development of thin palladium based membranes for obtaining pure hydrogen
- developing carbon-based membranes that operate at low temperatures and with high selectivity
- producing a conceptual design for a “hybrid” membrane separation system comprising a carbon membrane first stage followed by a palladium alloy membrane for use in a 100m^3/hr hydrogen refuelling station (see figure on this page). This system exploits the advantageous properties of each type of membrane so as to optimise overall performance
- carrying out a cost analysis of the membrane system and benchmarking performance and costs against commercial PSA systems.



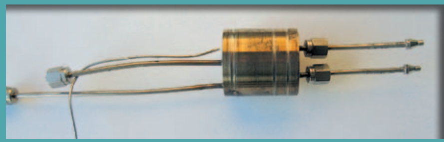
Conceptual membrane separation scheme for NATURALHY

Currently commercially available palladium membranes are conventionally “thick” tubular membranes and are very expensive. The NATURALHY approach has been to prepare extremely thin membranes both to increase flux and to reduce costs. Efficient palladium membranes have been developed using electroless plating to produce 3μm thick membranes, while magnetron sputtering has been used to deposit thin palladium/silver alloy membranes onto smooth uniform substrates. These membranes operate at 300°C with good hydrogen flux, high recovery and 100% selectivity for hydrogen. Carbon based membranes have been produced by pyrolysing hemicellulose. These membranes have been shown to have greater permeability with better selectivity (up to 98%) than conventional polymeric membranes; in addition they operate at temperatures between 30° and 90°C.

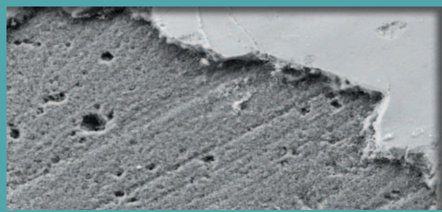
By combining the best characteristics of each of these membranes into a hybrid scheme, it has been possible to obtain an increase in efficiency and flexibility together with lower costs for separation. Depending on process conditions the carbon membrane can deliver up to 98% pure hydrogen, while the palladium membrane delivers pure hydrogen. Thus, the system can provide different hydrogen specifications depending on end user requirements. By using the carbon membrane, most of the separation is carried out at almost room temperature and, subsequently, the feed to the palladium membrane has very high hydrogen content, thereby improving the driving force and reducing, substantially, the palladium membrane surface area required.

Analysis of costs shows that the hybrid system, including ancillaries, is potentially cheaper than separation by PSA. Small scale PSA systems are currently under development. However, as with all PSA systems, separating hydrogen from streams with a hydrogen content less than 40% is problematic and requires additional facilities; the options are two PSA units in series, or, a carbon membrane (as with the hybrid concept) to concentrate the hydrogen level in the feed before the final PSA unit.

Gas quality issues have been considered, both in the case of adding hydrogen to the natural gas network and also the effect on downstream gas quality as hydrogen is withdrawn by end users. In a scenario where, for example, 25% hydrogen is added, by volume, to natural gas, end users at different points in the network may take out hydrogen at different quantities and qualities. This will have an effect on the gas quality of the remaining natural gas/hydrogen mixture, although analysis shows that the downstream gas quality will not be adversely affected since the Wobbe index and heating value will not be outside the statutory requirements.



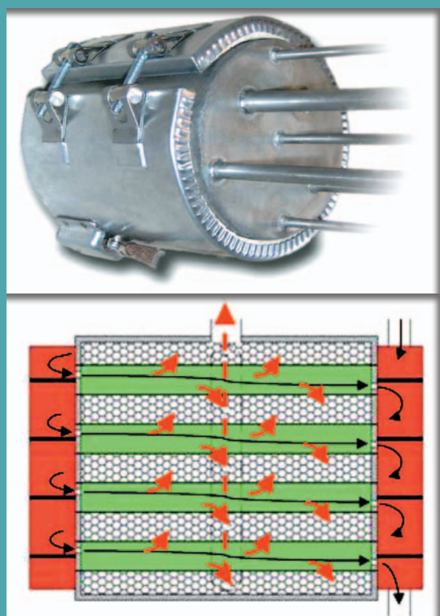
Pd membrane laboratory test module



Electron micrograph showing commercial ceramic support with defects and the effect of applying more uniform porous ceramic layer

Pd thin film membrane supported on tubular ceramic substrate

Hollow fibre carbon membrane



Packaged separator module integrating the membranes & heating system, and showing the internal flow pattern

10

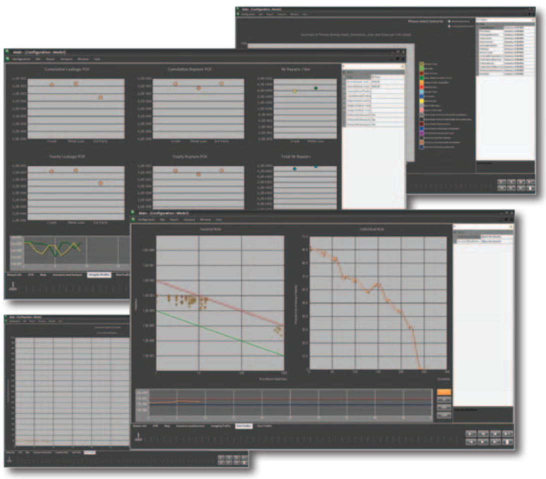
How to assess a specific network for the NATURALHY concept: the Decision Support Tool

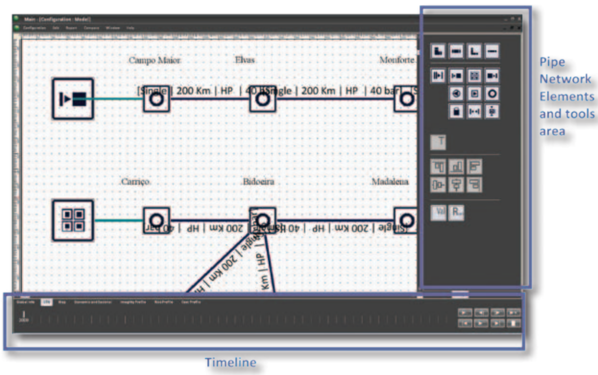
The NATURALHY project delivers a massive amount of information on the economics, societal and environmental aspects of transporting hydrogen over a natural gas transmission network and on a wide range of materials' properties and behaviour, on separation membranes performance and costs for several end user applications, such as industrial end users, filling stations, etc., on pipeline integrity and on gas transport network safety performance when carrying a mixture of hydrogen and natural gas.

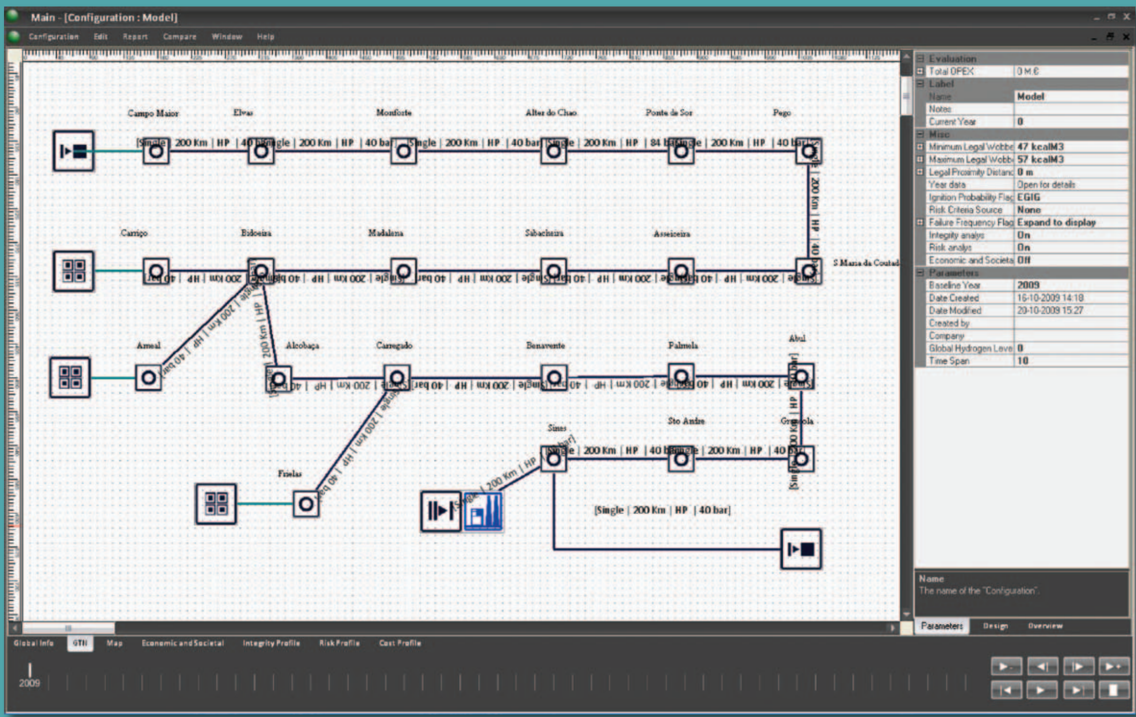
The NATURALHY DST (Decision Support Tool) has been devised in order to enable a natural gas pipeline operator to perform a "what-if" analysis on what happens to a specific Gas Transport Network (GTN) when specific hydrogen percentages are transported. The DST is a PC-based software tool which enables a company to introduce a configuration layout of a specific gas transport network or section of a network and evaluate the consequences of adding hydrogen and compare it with any other configuration over a number of active years.

It must be stressed that the DST is focused on an overall and general type of analysis and not on replacing, for instance, commercially available pipeline integrity management systems which carry out integrity analysis to a much greater level of detail. In addition, the considerable amount of detailed information on actual pipeline conditions and behaviour that is required in order to enable a more thorough analysis is either simply not available at gas company level or requires a data collection cost that is not acceptable for the resulting increase in accuracy.

The DST has two main uses: to inform, through its Information Repository, the expected material and device behaviour when certain hydrogen per-







Typical configuration of a Gas Transport Network (GTN)

centages are applied and to simulate, using its "what-if" analysis capabilities, the actual pipeline degradation behaviour over certain periods of time with the option of applying, on the pipeline model, mitigation measures. Thus, the NATURALHY DST key goals are to;

▶ enable editing, analysis and annotation of a pipeline network, so relevant information may be found and extracted at later stages

▶ compute a comprehensive "what-if" analysis of applying different levels of hydrogen in the network.

The above-mentioned analysis comprises risk assessment, cost assessment, evaluation, and proposal of rules, guidelines and procedures that will mitigate the expected increase of risk and/or costs when applying the gas mixture to the pipeline network.

The GTN sub-form is provided to enable the user to lay out a complete GTN using a comprehensive toolbox provided by the DST.

The DST is able to draw a map of the GTN so the user may actually see in the layout where sections cross population areas and establish more accurate risk distances (e.g. proximity to population densities).

The DST presents several "dashboards", for life cycle and socio-economic assessment, for safety and for integrity. With the exception of the life cycle and socio-economic assessment, all analyses are time dependent and show the evolution of the GTN properties over time.

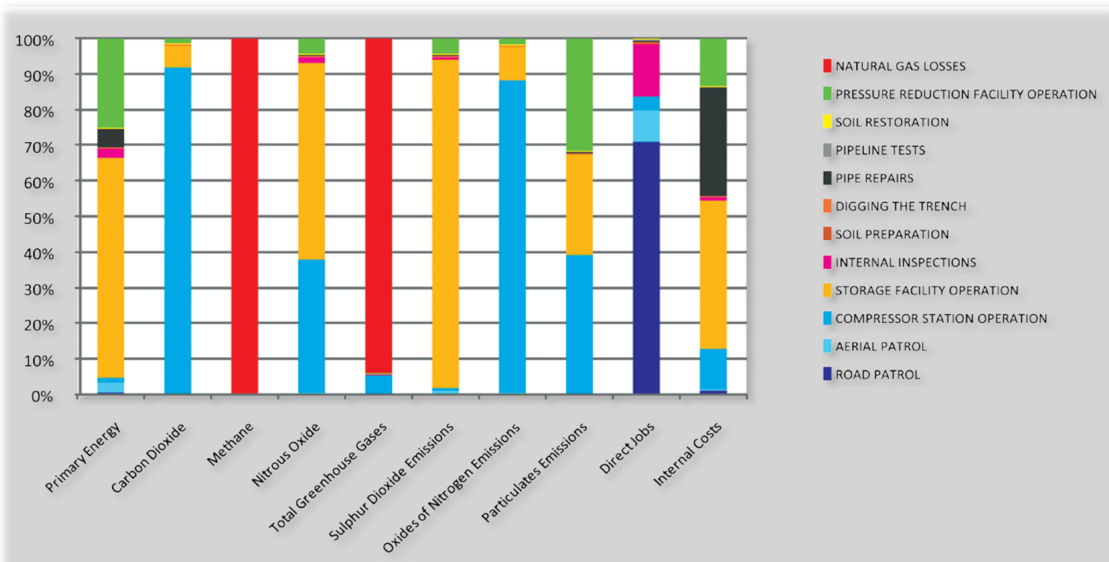
Each of the dashboards displays a specific analysis that is carried out by the NATURALHY DST. It is through the dashboards that comparisons between a GTN with or without hydrogen can be performed. The DST is extremely flexible and is able to carry out GTN simulation and comparison of any two configurations over a period of up to 50 years, yielding cost, safety and integrity calculations for all selected sections.

11

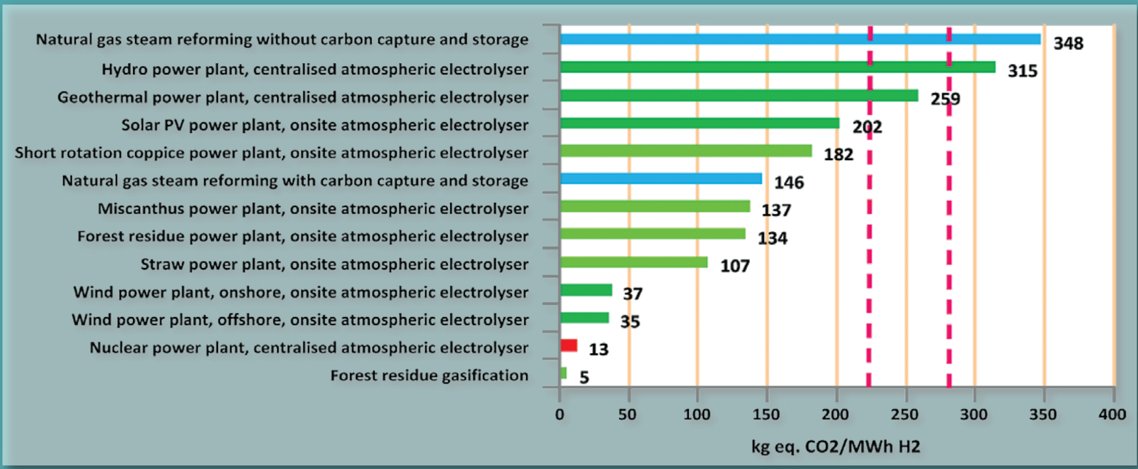
What are the overall benefits of adding hydrogen to natural gas?

The potential benefits of adding hydrogen have been addressed in the NATURALHY Project through life cycle and socio-economic assessment. This has involved establishing standard procedures for calculating various environmental impacts, economic costs and employment implications of existing and possible future energy systems. In particular, these procedures determine primary energy inputs (as indicators of energy resource depletion), carbon dioxide, methane and nitrous oxide emissions (as prominent greenhouse gas emissions associated with global climate change), sulphur dioxide, oxides of nitrogen and particulate emissions (as pollutants affecting urban air quality), internal economic costs, and direct and indirect jobs in the European Union. By adopting a systematic and transparent approach to these calculations, it has been possible to quantify benefits and communicate them in a convincing manner.

The starting point for this work was a review of life cycle and socio-economic assessment studies at the beginning of the NATURALHY Project. Subsequently, a standard format for calculations was devised, based on MS Excel workbooks, and an associated guide was prepared. From this, workbooks for relevant technologies were assembled both as stand-alone files and for incorporation into the DST. The most important workbooks are those which describe the existing natural gas network and its operation with the addition of hydrogen. The workbooks for the existing natural gas network



Breakdown of Energy, Emissions, Jobs and Costs per Unit Output of Natural Gas Network Operation for Large Users

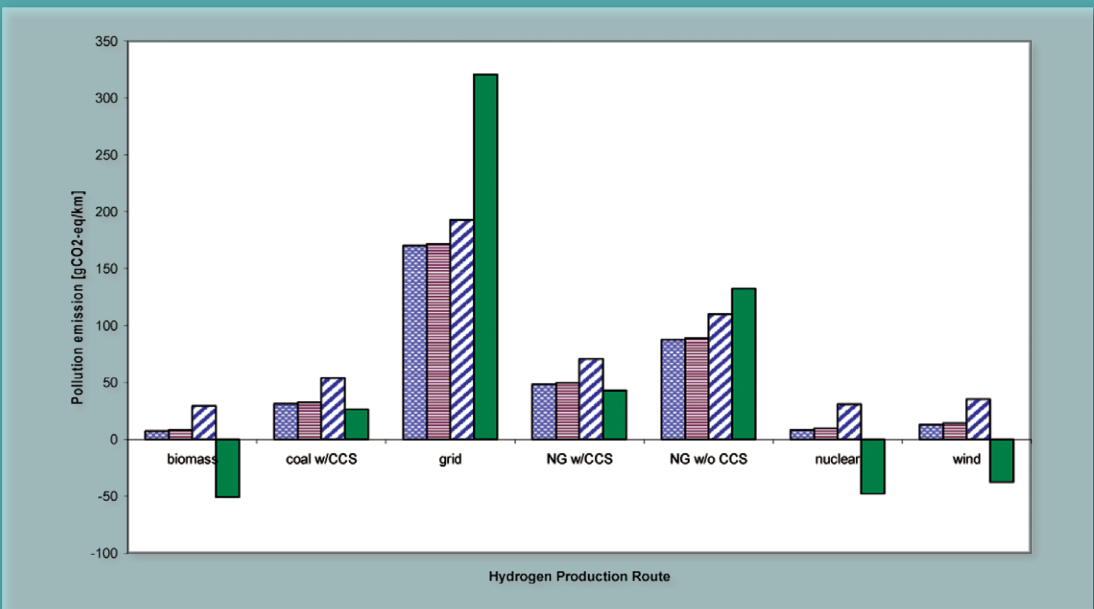


Total Greenhouse Gas Emissions for Hydrogen Production

were needed to provide a baseline against which the addition of hydrogen could be compared in terms of relative changes in environmental impacts, economic costs and employment implications. Outputs are generated in numerical and graphical formats, giving absolute values and relative contributions, for example to natural gas delivery by the network to large users (see the figure in page 24).

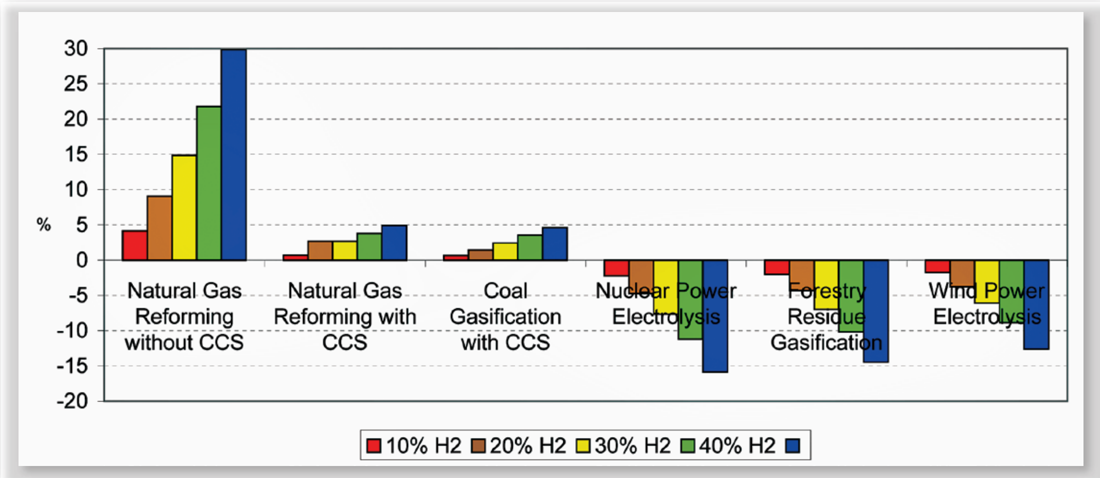
The workbooks for the existing natural gas network cover the supply of natural gas, and the construction, operation and maintenance, and decommissioning of the network. The actual details of these workbooks are based on a practical balance between appropriate representation of a real natural gas network and demands on user data input requirements. In particular, the components of a natural gas network have been simplified into a transmission (high pressure) system (with head stations, pipes, compressors and storage facilities), a regional distribution (medium pressure) system (with pipes and large pressure reduction facilities), and a local distribution (low pressure) system (with pipes). Aspects of these systems, such as different pipe lengths, diameters, wall thicknesses and typical materials, can be varied to simulate existing networks. Both design details and default values were provided for these workbooks by gas utilities which were NATURALHY Project partners.

The workbook which describes the operation of natural gas networks with the addition of hydrogen was assembled using results generated by other NATURALHY project activities. In



Total Greenhouse Gas Emissions for Hydrogen Delivery by Truck, Dedicated Pipeline and the Existing Natural Gas Network (NATURALHY approach) particular, the procedure for adjusting leakages for the addition of hydrogen was provided by studies conducted on safety, incorporating some of the results from research on durability. Crucial information on the effects of hydrogen on the frequency of internal pipe inspections and subsequent repairs was supplied from activities on integrity. The source of essential performance data on hydrogen separation technologies and the effect of hydrogen on appliances derived from research on end-use.

In order to complete analysis of potential benefits, it was also necessary to add evaluation of methods for producing hydrogen. For convenience, this was achieved by creating a Library of Results which included available data on a variety of different hydrogen generating technologies. This enables comparison of results such as total greenhouse gas emissions, measured in equivalent carbon dioxide, for a range of hydrogen production technologies with the emissions factors for the conventional supply, delivery and combustion of natural gas by different users (bounded by the pink dotted lines as illustrated in the first figure of page 25).



Change in Total Greenhouse Gas Emissions for Natural Gas/Hydrogen Delivery to Large Users

Specific details of the source of hydrogen, where it is injected into the existing natural gas network, and whether and how it is separated from the subsequent mixture determine the occurrence and magnitude of benefits.

The addition of hydrogen to natural gas can make a significant reduction in total greenhouse gas emissions if the hydrogen is sourced from certain forms of biomass (forestry residues, straw and miscanthus), wind power (both onshore and offshore) and nuclear power. Depending on circumstances, hydrogen production from fossil fuels with carbon capture and storage also offers some advantages. However, reductions in total greenhouse gas emissions with these sources of hydrogen are generally lower. Additionally, there may be no benefits in terms of decreased primary energy demand or energy resource depletion, although implications for energy security are governed by the location of these sources of fossil fuels. Potential benefits of extracting hydrogen from the mixture depend on the actual performance of the separation technology and the subsequent use of the hydrogen (including its required purity) and the residual gas (which still contains some hydrogen). However, overall air quality benefits (especially lower sulphur dioxide, oxides of nitrogen and particulate emissions) can arise if hydrogen is subsequently used in transportation and displaces conventional diesel fuel. As with the so-called "greening of gas", the relative benefits of delivering hydrogen, say for use in road vehicles, depends on the various considerations, especially the original source of hydrogen.

12 Concluding remarks

NATURALHY has been a significant project, with considerable time and effort dedicated to testing and production of what is a vast array of data, much of it completely new. It is almost impossible to summarise the project in a short space and, in fact, unfair to do so. Indeed care must be taken in looking at summary results from this project and jumping to simple conclusions.

The data are often complex, with many provisos, given the immensity of what has been attempted and, in general, successfully achieved. The reader is, therefore urged not to grasp at what looks like a favourable or even an unfavourable result, without a deeper analysis of the specific system under consideration.

Nevertheless, some attempt must be made to condense the key findings of NATURALHY project. And, whilst they are presented below, they should be read while bearing in mind the qualifying remarks outlined previously:

1. With regard to pipeline durability, results show that effects on pipe materials used in the natural gas grids, caused by hydrogen, can be mitigated by appropriate measures. Modifications to maintain a safe and reliable supply of customers with natural gas / hydrogen mixtures will mainly be necessary for the transportation pipelines made of steel, but importantly, no "show-stoppers" have been identified.

2. Considering integrity, the material investigations revealed that additional measures will be required to ensure the integrity of steel pipelines, when hydrogen is transported by the existing natural gas system. Consequently the pipeline integrity management systems (PIMS) in place need to be adapted. Modifications will be necessary for wider aspects of the existing PIMS as defects that are currently not the centre of attention need to be considered, when hydrogen is transported. Summarising the results overall, appropriate pipeline integrity management can be put in place to permit the transportation of natural gas and hydrogen mixtures.

3. It was anticipated that adding hydrogen to the gas infrastructure may affect both the likelihood and severity of untoward events and,

Gas flame inside the gas boiler

hence, potentially increase the risk to the public. In this regard, the NATURALHY project has established:

▶ that escapes of natural gas/hydrogen mixtures within buildings behave in a similar way to natural gas, in terms of the nature of the gas/air mixture produced. However, the gas concentration and volume of the accumulation increases as hydrogen is added but these increases are slight for hydrogen addition up to 50% by volume

▶ within buildings, severity of explosions increases if hydrogen is added to natural gas. However, the increase is only slight for hydrogen addition up to 20%. Analysis has suggested that the explosion frequency could increase by up to a factor of 2 as a result of adding up to 20% by volume hydrogen to natural gas. However, the current risk is very low and even with doubling the risk remains within generally acceptable limits

▶ from the point of view of the pipeline operator, the principal hazard posed by the failure of transmission pipelines is that of a large fire. Results suggest that the addition of hydrogen increases the risk to an individual at locations near the pipeline but decreases the risk at locations further away, as the extent of the hazardous region is reduced

▶ pipeline operators need to assess the background level of leakage from their pipeline networks, since methane is a greenhouse gas. A study of the expected background level of leakage has shown that the level of leakage overall is very small and poses no hazard from a safety point of view. Indeed, the addition of hydrogen results in a slight decrease in the level of methane emissions to the atmosphere from the gas infrastructure, which is beneficial from an environmental perspective

4. For domestic appliances, personal health and home safety are at stake and tens of millions of appliances are involved in any given country; as a consequence, particular attention has been paid to domestic appliances and it is important to note that

▶ the maximum hydrogen concentration for the domestic market in any country is determined by the safe operation of properly adjusted conventional domestic appliances as well as by the local conditions of natural gas quality (range and current value of Wobbe Index)

- for properly adjusted appliances and favourable conditions of natural gas quality, conventional domestic appliances can accommodate up to 20% of hydrogen

- for poorly adjusted appliances and/or unfavourable conditions of natural gas quality, no hydrogen admixture is allowed

- stationary gas engines and gas turbines need readjustment and/or modification

- feedstock processing and industrial combustion applications require case-by-case consideration.

5. Gas quality issues have been considered, both in the case of adding hydrogen to the natural gas network, and also the effect on downstream gas quality as hydrogen is selectively withdrawn by end users. In a scenario where end users at different points in the network may be taking out hydrogen at different quantities and qualities, there will be an effect on the gas quality of the remaining mixture. However, analysis shows that the downstream gas quality will not be adversely affected since the Wobbe index and heating value will not be outside the statutory requirements.

6. The Decision Support Tool (DST) has two functions: to inform what is expected in material and device behaviour at particular hydrogen percentages; and to simulate, using its "what-if" analysis, the actual pipeline degradation behaviour over certain periods of time.

The analysis comprises risk assessment, cost assessment, evaluation, and proposal of rules, guidelines and procedures that will mitigate the expected increase of risk and/or costs when applying the gas mixture to the pipeline network.

It also provides a comprehensive toolbox that enables the user to simulate a Gas Transport Network (GTN) to enable comparisons between a GTN with or without hydrogen addition. The DST is extremely flexible and is able to carry out GTN simulation and comparison of any two

Gas Wellhead

Natural gas pump and distribution station

configurations over a period of up to 50 years, yielding cost, safety and integrity calculations for all selected sections.

7. The potential benefits of adding hydrogen to the natural gas system have been addressed by life cycle and socio-economic assessment and it has been possible to quantify benefits. However, the following conclusions are, necessarily, qualitative:

- the addition of hydrogen to natural gas can make a significant reduction in total greenhouse gas emissions if it is sourced from certain forms of biomass (forestry residues, straw and miscanthus), wind power (both onshore and offshore) and nuclear power. Depending on circumstances, hydrogen production from fossil fuels with carbon capture and storage (CCS) also offers some advantages. However, reductions in total greenhouse gas emissions with these sources of hydrogen are generally lower
- potential benefits of selective extraction of hydrogen depend on the actual performance of the separation technology and the subsequent use of the hydrogen (including its required purity) and the residual gas (which still contains some hydrogen). However, overall air quality benefits (especially lower sulphur dioxide, oxides of nitrogen and particulate emissions) can arise if hydrogen is subsequently used in transportation and displaces conventional diesel fuel
- the addition of hydrogen can be an effective means of "greening" natural gas so that the mixture is used directly in existing appliances for heat production and electricity generation. With this option, the potential benefits are mainly as a practical measure for mitigating global climate change and increasing energy security, depending on the original source of the hydrogen.❖

Silver Gas Plant Towers

Three natural gas burners with bright blue flames inside an operating gas furnace

Project Co-ordinator
N.V. Nederlandse Gasunie

Work Package Leaders:
University of Oxford,
GDF SUEZ,
Loughborough University,
DBI-GUT,
Instituto de Soldadura e Qualidade (ISQ),
GERG - The European Gas Research Group,
EXERGIA

Other Project Partners:
BP Gas Marketing,
Centro Sviluppo Materiali (CSM),
Cogen Europe,
Commissariat à l'Energie Atomique (CEA),
Compagnie Européenne des Technologies de l'Hydrogène (CETH),
Computational Mechanics International (CMI),
Danish Gas Technology Centre (DGC),
TNO Science & Industry,
Ecole Nationale d'ingenieur de Metz (ENIM),
Energy Research Centre of the Netherlands (ECN),
General Electric PII,
UCB Högskolan i Bors,
Institut Français du Pétrole (IFP),
Istanbul Gas Distribution (IDGAS),
National Grid,
National Technical University of Athens (NTUA),
Naturgas Midt-Nord,
Nederlands Normalisatie-Instituut (NEN),
Norwegian University of Science and Technology (NTNU),
Planungsgruppe Energie und Technik (Planet),
Hellenic Gas Transmission System Operator (DESFA),
SAVIKO Consultants,
Shell Hydrogen,
SQS Portugal,
Statoil,
Technical University Berlin,
The Health and Safety Executive (HSE),
Total,
Turkish Scientific and Technical Research Council (TUBITAK),
University of Leeds,
X/Open Company Ltd

NATURALHY
is an Integrated Project funded
by the European Commission's
Sixth Framework Programme (2002-2006)
for research, technological development
and demonstration (RTD)