Strategic Justification
of the Research Project

"Preparing for the hydrogen economy by using the existing natural gas system as a catalyst (NATURALHY)"

This project is supported by the European Commission within the programme on Sustainable Energy Systems of the Sixth Framework Programme, and has been recognised by the International Partnership of the Hydrogen Economy.

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CONTENT

1 Executive Summary

Hydrogen is widely seen as an important sustainable energy carrier in the future. Hydrogen can be produced from sustainable energy sources such as wind and wave energy, by biomass gasification or it can be a by-product of chemical processes. An increasingly important role for hydrogen is in relation to the gasification of coal with or without power production.

The transition towards the situation in which hydrogen will be fully integrated in the energy mix will be lengthy (decades), costly, and will need a significant research and development effort. Next to production and end user facilities for hydrogen and hydrogen containing gases, a delivery system of sufficient capacity is needed that connects production and end user, and that matches production and demand on hourly, daily, and seasonal basis. Network companies are interested in the addition of sustainable produced gases to the natural gas networks, as this leads to greening of their gas supply business, opening up new business opportunities and improving corporate environmental image.

Consequently, examination of the potential of using the existing natural gas pipeline system for the widespread delivery of hydrogen (containing gases) in Europe is a necessary and important activity, the first element of which is the definition of the conditions under which hydrogen and hydrogen-containing gases can be added to the existing natural gas networks. Adopting this strategy will initiate the transition towards the widespread utilisation by end-users of pure hydrogen as well as gases that contain a certain percentage of hydrogen. Thus the NATURALHY project addresses the greening or decarbonisation of existing natural gas supply operations by

- replacing a proportion of the natural gas supplied to EU end-users with hydrogen produced from sustainable sources;
- and by providing the opportunity to initiate local pure hydrogen centres (for example local hydrogen refuelling stations) by extraction of hydrogen from the natural gas/hydrogen

However, pipeline companies must be absolutely convinced that the addition of hydrogen to their sophisticated and expensive systems can be achieved with acceptable consequences. In addition the chemical and physical properties of hydrogen and natural gas differ significantly, and this may have an impact on safety in relation to the delivery of gas, the use of gas and the integrity of the network. These issues are at the core of the NATURALHY project.

The NATURALHY project investigates the conditions under which hydrogen (pure or as a part of a hydrogen containing gas mixture) can be added to natural gas with acceptable consequences for safety, life cycle and socio-economic aspects, durability of the system, gas quality management and performance of end-user appliances. Membranes will be developed to enable the selective extraction of hydrogen from the hydrogen/natural gas mixture for use by hydrogen powered equipment. The life cycle and socio-economic assessment aspects of the mixing option of pure hydrogen will be mapped out, and compared to current natural gas and related energy systems, to proposed transitional natural gas/hydrogen systems, and to future 100% hydrogen systems, from source to point of use. Particular attention is being paid to forging strong links between the project, stakeholders and other relevant research projects and initiatives, to ensure that the NATURALHY objectives and activities remain both relevant and at the vanguard of a sustainable energy economy.

2 Introduction

Hydrogen is an important element of a sustainable energy society: it can be produced in many ways including electrolysis of water, using electricity produced from wind or solar energy, or gasification of biomass and coal. It can be an important part of the synthesis gas (syngas) produced in a coal or biomass gasifier, or of (waste) gases of industrial processes. Pure hydrogen can be converted by fuel cells into electricity with high efficiencies. The pollutant emissions from the controlled combustion of hydrogen are very low.

More particularly, it is believed that utilizing hydrogen and gases containing hydrogen will:

- make a significant contribution to security of supply, by utilizing locally available primary energies like gasification of biomass;
- reduce CO_2 emissions, by replacement of fossil fuels with hydrogen from renewables, or from fossil fuels with CO_2 sequestration or by the implementation of the process for removing carbon (as a solid) from natural gas to produce "hydrogen-enriched natural gas" as proposed by Atlantic Hydrogen[1]. These options contribute to de-carbonisation and greening of our energy economy. .
- increase the options for utilizing (waste) gases that contain hydrogen, and enable the development of power plants based on coal and biomass gasification, in spite of the fact that the gasification process demands a high load factor. This will involve using carbon capture and storage (CCS) to reduce greenhouse gas emissions;
- improve local air quality, by replacing petrol and diesel in cars and buses.

As hydrogen can be converted into electricity and vice-versa, with high efficiency, it has potential for the storage of electrical energy (e.g. in case electricity production from wind energy exceeds the demand).

Hydrogen can be used as a pure gas (for example, in fuel cells, combustion engines and turbines) and also as a mixture with natural gas in combustion engines, stationary applications and in some fuel cells.

In order to stimulate the transition towards sustainability the European Commission adopted the EU Directive 2003/55/EC, which states that "*… taking into account the necessary quality requirements, biogas and gas from biomass or other types of gas are granted non-discriminatory access to the gas-system, provided such access is permanently compatible with the relevant technical rules and safety standards. These rules and standards should ensure, that these gases can technically and safely be delivered into, and transported, through the natural gas system and should also address the chemical characteristics of these gases…*" Although not explicitly stated in this Directive, it also applies to biogas containing hydrogen. In addition, it can be argued that "*… other types of gas*" includes hydrogen produced, for example, as a by-product of a chemical process. Moreover, this Directive motivates the natural gas industry to prepare itself for a role in the delivery of hydrogen and of hydrogen containing gases.

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[1] For details, see www.atlantichydrogen.com.

Gas network operators are very interested in de-carbonising natural gas and in adding sustainable produced gases to the natural gas infrastructures since this leads to de-carbonising of their business operations, provides new business opportunities as well as improving corporate image.

3 Transition barriers and challenges

The transition towards a scenario in which hydrogen or hydrogen-containing gases are a sustainable, reliable and cost-effective energy option has begun and is progressing. However, there is a "chicken and egg" problem concerning the production, delivery and end use chain. For example, it makes no sense to install facilities that produce (gases containing) hydrogen if there is neither a hydrogen (pure or mixed) demand nor a delivery system in place to make it available to potential end users. As long as there is no view on a long-term economic perspective for the production, delivery and use of large volumes of hydrogen, there will be a reluctance to invest in projects in which hydrogen plays an important role, except in some limited demonstration projects, probably with some substantial financial support from government(s).

Although significant progress has been made, crucial technical and economic barriers have still to be overcome before pure hydrogen and gases containing hydrogen become a cost-effective and environmentally effective alternative energy carrier that will both be widely available and offer a high level of security supply.

For safe, environmentally friendly and cost-effective transport and distribution of large quantities of gas, pipeline systems are generally considered superior when compared with, for example, trucks and trains (concerning the cost aspect, the work of M. Ringer and W. Amos of the National Renewable Energy Laboratory, and of A. Elgowainy of Argonne National Laboratory are relevant). The technical knowledge and components to construct high-volume delivery systems suitable for hydrogen (containing gases) are available. Indeed, there are already several industrial hydrogen networks in operation (Air Liquide, Linde, Air Products, NASA, Praxair). In 2004 there were 1450 km of low pressure hydrogen pipelines in the USA and 1500 km in Europe. However, key concerns in developing a new widespread pipeline delivery system suitable for hydrogen (containing gases) are construction costs, which can range from hundreds to several thousands of billion Euros on EU-scale, depending on the scenario (as described by P. Castello c.s. in the report EUR 21586 EN), the societal cost of the construction activities and the construction time (decades). Moreover, increasingly stringent land planning issues will prevent a quick development of a new pipeline.

The addition of sustainable produced gas in the natural network, the so called "greening of gas", is an option strongly supported by Governments and the pipeline companies. For instance the Green Gas working group in the Netherlands estimates that 8-12% of the natural gas could potentially be replaced by sustainable produced gas in 2020, 15-20% in 2030 and 50% in 2050. The currently produced sustainable gases consist of gas from fermentation processes (having high methane content). However, in the future, say after 2015, the majority of sustainable gases will be produced in gasification processes utilising biomass and/or coal (with CCS).

Gas from gasification processes basically consists of carbon monoxide/hydrogen mixtures (syngas). Using the catalytic methanation step, syngas is converted into Synthetic Natural Gas (SNG), mainly consisting of methane, but which might still contain a certain percentage of hydrogen. This is an exothermic process (206 MJ/kmol) in which a significant part of the latent energy is transferred into process heat. However, if the natural gas system is able to accommodate significant volumes of hydrogen, the methanation step could be replaced by the water-gas shift reaction (also exothermic, 42 MJ/kmol). This reaction, widely used in industrial hydrogen production, reacts the CO/H2 mixture with steam to produce a CO2/H2-mixture, and after removal of the CO2, hydrogen remains.

This approach represents a real opportunity to bring the NATURALHY vision to fruition, accelerate the introduction of hydrogen into natural gas grids, and enable operators to gain operational experience and assess impacts of distributing hydrogen containing natural gas.

4 The potential of the existing natural gas grid for 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 the existing assets, including the existing natural gas 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.

As explained further in this chapter, in general a network designed for natural gas cannot be used for pure hydrogen for a number of reasons without modifications to the network components or the way it is operated and maintained. However, the existing natural gas transmission, distribution and end used systems could be used for mixtures of natural gas and hydrogen given appropriate modifications. The mixture can be used as such and, if required, hydrogen appliances could be fuelled with “pure” hydrogen by developing devices to extract hydrogen selectively from the mixture.

The accommodation of gasification gas in natural gas networks is very interesting in the framework of coal gasification facilities for power production. These facilities need to be operated at a high load factor (low ability to adjust production capacity), and consequently at low electricity demand, there is a surplus of syngas. It would really be an advantage if this surplus, after being converted into hydrogen by for instance the water-gas shift reaction, could be accommodated in the high capacity natural gas network! An alternative option concerns greening of gas by accommodation of hydrogen produced from a surplus of sustainable produced electricity including electricity from wind energy.

Of course, for the accommodation of gases that contain a certain percentage of hydrogen it is important that the physical and chemical characteristics related to the composition of the gas fit sufficiently with the characteristics of natural gas, and do not initiate un-acceptable risks for for instance the integrity of the gas system.

The NATURALHY project focuses on the option of adding hydrogen to natural gas in the existing network, either by implementing appropriate modifications to the network, or through changes in the way it is operated and maintained. However, the results are also relevant for examining the potential of using the existing natural gas infrastructure for pure hydrogen.

In general, the transmission and distribution of hydrogen require different materials from those used for natural gas. In addition, modifications will need to be made to operating conditions, condition monitoring and integrity management strategies in cases where a network, not designed for hydrogen, is used to convey gases containing hydrogen.. There has been other similar activity, reported elsewhere[2] concerning the use of existing oil pipelines for hydrogen transmission in the US Gulf-area, but this differs significantly from NATURALHY in that:

- the oil pipelines were to be operated with hydrogen at significant lower pressures than their initial design pressures;
- the safety approach with regard to the design of gas pipelines in the US is different to that of Europe. In the US a prescriptive approach to safety is taken based on industry guidelines and regulations. In Europe a risk based approach is taken whereby operators must demonstrate that the risks are As Low As Reasonably Practicable (ALARP).

4.1 The potential impact

Using the existing natural gas system for mixtures of natural gas and hydrogen will have the following main points of impact:

- **Environmental benefits** -
  In 2007, the total primary energy consumption in the EU27 countries amounted to 1,796 MTOE[3] of which 442 MTOE (25%) was provided by natural gas. If 1%[4] of the energy content of the natural gas were replaced by hydrogen (produced CO_2 free), the total CO_2 emission of the EU27 would be reduced by about 8.5 Mtons/year. In case said volume of hydrogen would replace the same amount of latent energy in oil or coal, the savings would amount to 12.7 Mtons/year for oil and 15 Mtons/year for coal. So, although the maximum percentage of hydrogen that can replace natural gas is the subject of research, the potential of decarbonisation or greening of natural gas by hydrogen/natural gas mixtures for the reduction of CO_2 emissions is significant.
  If the hydrogen is a part of sustainable produced gases (e.g. from the gasification of biomass), the contribution of the other combustible components to the caloric value, will lead to a further increase of CO_2 reduction.
- **Macro economic benefits**

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[2] "Conversion of Existing Hydrocarbon Pipelines for Hydrogen Service", Campbell, International Pipeline Conference, Calgary, 2004

[3] 1MTOE = 1 million tones of oil equivalent = 41.86 x 10^{15} J (Net Calorific value)

[4] 3% by volume

As already mentioned, the cost of a new widely spread hydrogen pipeline system would be enormous. If the existing natural gas infrastructure could be used to carry hydrogen to some extent, this would result in significant financial savings.

- **Catalyse hydrogen developments**
  Using existing high capacity and broadly spread assets for connecting hydrogen producers to hydrogen end users in the short term and at relatively low capital cost, will help break the chicken and egg problem and will provide an important impetus for the development of hydrogen as an energy carrier.
- **Increase public acceptance/Social of socio-economic benefits**
  Using the excellent safety record of the natural gas industry as a vehicle, the delivery of hydrogen/natural gas mixtures will help to increase the public acceptance of hydrogen.

4.2 The natural gas system

The European natural gas system (see figure 1) is very well developed and consists, *inter alia*, of 1.8 Mkm (EU27) pipelines of which 156,000 km concern high-pressure transmission pipelines. In addition, 129 (EU27) storage facilities with a total working volume of 76,000 Mm^3 are in operation. (Eurogas report '07-'08).

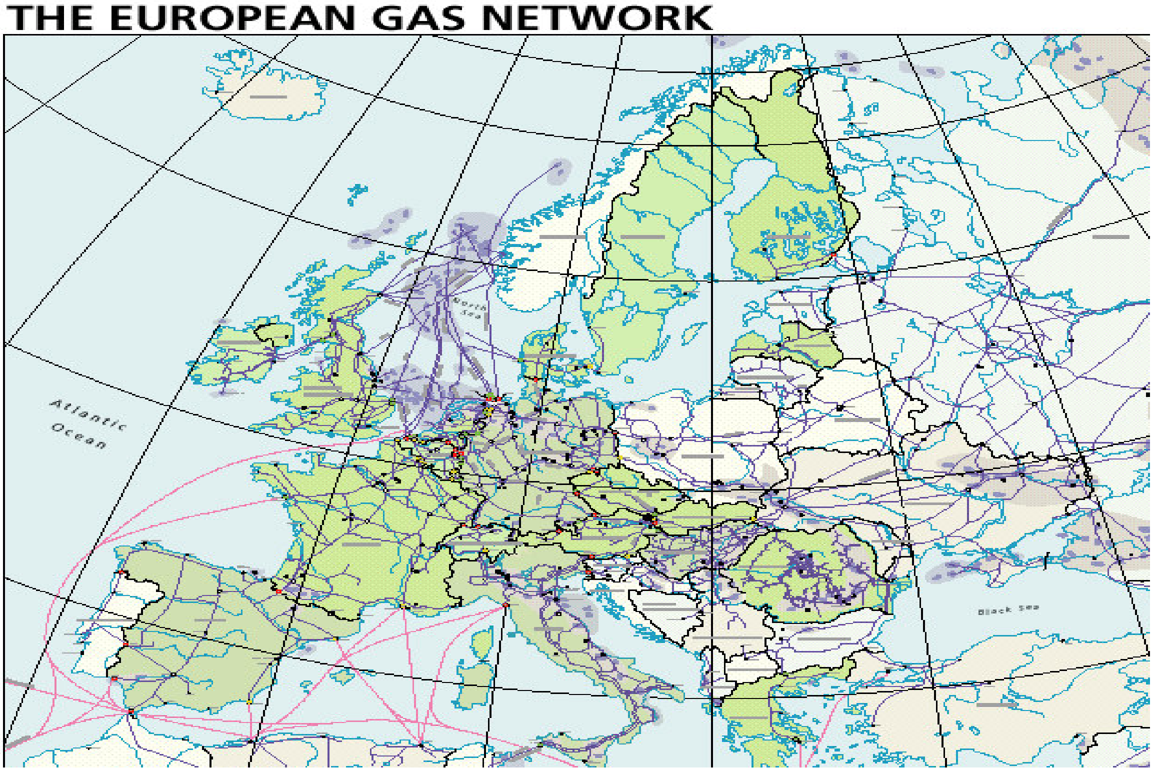

Figure 1: The existing European high pressure natural gas transmission network

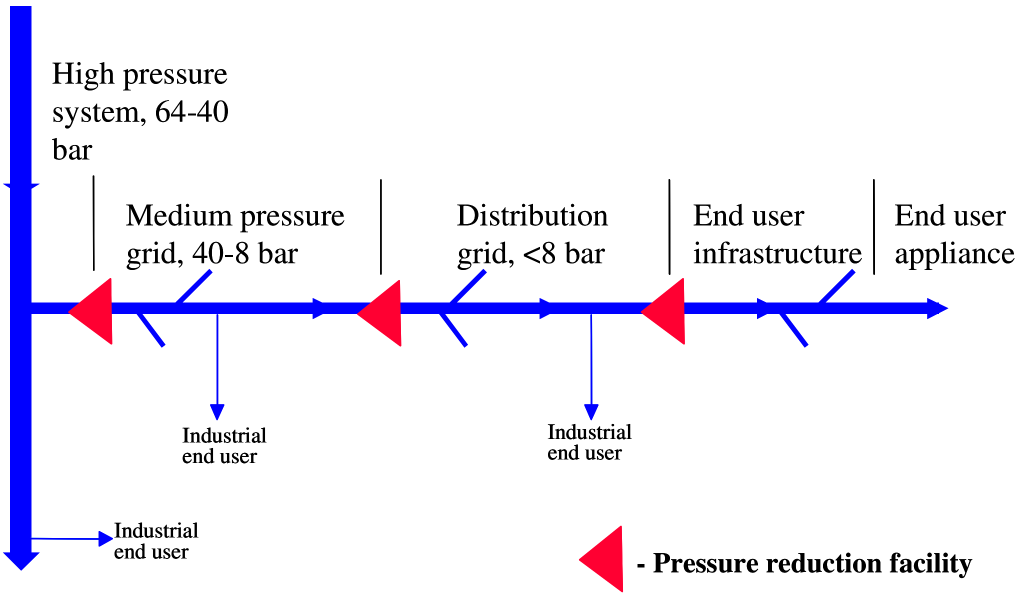

Figure 2: Schematic view of the different parts of a natural gas delivery system.

The following distinct parts of the existing natural gas chain (see figure 2) and their characteristics can be identified (the pressure regimes as just indicative, and may differ from country to country):

Part of the N.G. system	***Operating pressures [bar]***	***Active components (besides valves and pressure regulators)***	***Material of pipelines***	***Connected end users***
Natural gas production and treatment facilities	>65	Various	Steel	-
High pressure transmission systems	<70 and >40	Compressors, LNG-facilities, underground storages, gas blending stations	Steel	Power plants, iron mills, large chemical plants using natural gas as feedstock, etc
Medium pressure transmission system	<40 and >8	-	Steel	Chemical plants, ceramic industry, district heat & power plants (WKK-facilities), etc
Distribution grid	< 8	-	Steel, cast iron, polyethylene (PE), PVC	Offices, domestic end users, greenhouses etc.
End user infrastructure	< 8	-	Copper, polyethylene (PE)	-

In general, stakeholders demand the following minimum requirements for the operation of a delivery system:

- sufficient capacity to fulfil the demand on extreme cold days (this includes the crucial role for matching the different patterns of production and end use);
- high level of security of supply (related to the previous point);
- long term economic viability perspectives (which includes market perspectives);
- widely spread;
- high level of safety;
- high level of acceptance by the public.

Paragraph 4.4 and chapter 5 explain how and to which extent these requirements are addressed in the NATURALHY project.

4.3 Differences between the properties of hydrogen and natural gas

The physical and chemical properties of hydrogen differ significantly from those of natural gas. The following table shows some indicative values at standard conditions of properties relevant for the gas chain from source to end user (sources: Air Products, HyWeb, OCEES, ORNL).

Property	Hydrogen	Natural gas
Caloric value [MJ/m^3]	13	38
Density [kg/m^3]	0.09	0.8
Air volume needed for the combustion of 1 m^3 [m^3]	2.5	8.5
Ignition energy gas/air mixture [mJ]	0.02	0.3
Ignition temperature [^{o}C]	585	540
Flammability limits gas/air mixture	4-75%	4.7-16.6 %
Viscosity [µPa.s] (1 bar, 20^{o}C)	8.8	110
Flame velocity [cm/s]	350	40 (methane-air)
Diffusion coefficient in air [cm^2/s]	0.6	0.16
Diffusion coefficient in PE (20%H2/80%CH4 mixture at 40°C and 20 bar) [cm^2/s]	3,6 x 10^{-6}	1,7 x 10^{-7}
Diffusion coefficient in steel [cm^2/s](100^{o}C)	2.5 x 10^{-7}	Nil

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. Even the addition of a certain percentage of hydrogen to natural gas will have a direct impact on:

- the combustion properties;
- diffusion into materials;
- the behaviour of the gas mixture in air.

These aspects are considered further below.

4.4 The impact of hydrogen on the natural gas system

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, *inter alia*, the following aspects:

- **Safety related to the transmission, distribution and use of gas.** Assessment of gas safety is based on risk assessment, defined as the consequences of an event multiplied by the probability such event takes place. The consequences related to unintended gas releases, gas build up in rooms and gas clouds may change significantly as a result of the addition of hydrogen because of the differences of the combustion and dispersion characteristics of hydrogen and natural gas. The probability of an event might be affected by the changed combustion properties (e.g. decreased ignition energy, wider flammability limits of gas/air mixture) and the impact of hydrogen on the change of material failure.

  Aspects of pipeline systems, such as location, materials, wall thickness, safety devices, etc., are designed on the basis of risk assessments. For instance, the design criteria for a pipeline in a populated area differ from the criteria for a pipeline in the countryside. As hydrogen is added it will change the gas properties and, as a consequence, the related risks will change. An additional safety risk of using a natural gas system for hydrogen may arise from the fact that the potential leakage rate of hydrogen is much larger than that of natural gas through the same sized leak. This could be important in for instance (semi-) confined domestic rooms. Moreover, the efficiency of existing seals in a natural gas system is less for hydrogen than for natural gas.
- **Integrity of pipelines.** Hydrogen may diffuse into materials and change their mechanical properties. For example, hydrogen embrittlement of steel, leading to an accelerated growth of micro cracks, is a well recognised phenomenon. Hydrogen may also diffuse through polymers resulting in a significant loss of hydrogen. This may affect the integrity of the system and could also have an impact on safety. A related issue to be addressed concerns condition monitoring and repair techniques of the delivery system. Are the existing monitoring and repair techniques adequate to monitor and repair defects which are of no importance if the pipeline contains only natural gas, but which are crucial in the case where hydrogen is added?

Figure 3: “Intelligent pig” for the in-line inspection of transmission pipelines

- **Gas quality management**. It should be ensured that end users will remain supplied with gas that meets the contractual specifications in order to guarantee their safety, performance of end user appliances, and billing accuracy. Moreover, this is an issue if hydrogen is extracted from the mixture, and the remaining gas is supplied to end users further downstream;
- **The performance of end user appliances.** End-use appliances are designed for a certain set of gas characteristics (represented by the Wobbe index). Since the combustion properties change when hydrogen is added to natural gas, this may also affect the performance of end user appliances. Without appropriate modifications to natural gas appliances, there is an increased probability that flames will be extinguished or will ‘flash back’. Burners may be damaged, and there could be a risk of unintended gas releases and an increase in unsafe situations as a result of adding hydrogen. Particular industrial burners in, for example, the glass industry are very sensitive to changes of the combustion properties of the gas supplied. Adding hydrogen will also impact on industrial processes that use natural gas as a feedstock. For example, in ammonia production, the addition of hydrogen to natural gas may have a beneficial effect.
- **The energy capacity of the delivery system**: this aspect is explained in further detail in paragraph 4.5.
- **Gaseous (and energy) losses** during the transmission, storage and distribution. The permeability of the walls of underground storages and of pipeline materials etc. is higher for hydrogen than for natural gas. In addition, leakage from small leaks will be increased. Next to feasible safety aspects, these losses also have economic and environmental aspects.
- **The suitability of the compressors** in the transmission grid should be checked for the changed properties of the gas to be compressed.

It is difficult to specify a single, indicative figure for how much hydrogen can be added to the natural gas network, because:

- The natural gas network is very complex, and the capability of pipelines to accept hydrogen is determined by the capability of each individual pipeline segment, which may differ from segment to segment. The capability depends strongly on, amongst others, the material of the segment, the condition of the segment (scratches and other defects are crucial), the way the pipeline is operated, and the impact of added hydrogen on the outcome of a risk assessment. In fact the capability of a pipeline should be determined by the examination of each individual pipeline segment, considering its specific characteristics.
- The contractual conditions, including gas properties, of the gas supplied to end users must be fulfilled and, as there is a large variety of such conditions and of natural gases supplied over Europe, the maximum percentage of hydrogen that fits within the contractual limits will differ from place to place. Even for natural gas supplied within the contractual limits, the addition of hydrogen could lead to significant problems for end users (feedstocks, glass industry).

4.5 Capacity aspects

The natural gas system is designed for the maximum capacity that may be required, say, once every 50 years. As energy demand shows a pattern over the day, over the seasons and over the year, dynamic simulations are routinely used to optimise the layout and the dimensions of the systems. It should be noted that the delivery system not only moves gas from production to end user, but that it also adapts to the different patterns of supply and demand and it must be capable of coping with fluctuations in gas composition of the gases entering the system. “Capacity” is the key issue of a natural gas system to ensure a sufficiently high level of security of supply, both volume and gas quality.

If an existing pipeline system could be switched from natural gas to hydrogen and still be operated at the same maximum pressure, its maximum capacity (measured in energy terms) would be approximately one third less with hydrogen then with natural gas (the calorific value of hydrogen is about 1/3 of the value for natural gas, but hydrogen can be transported with lesser resistance than natural gas) (see for instance Air Liquide and P. Castello c.s.). For the same reason, it is anticipated that the addition of hydrogen to natural gas will reduce the capacity of a pipeline.

There are several options to be considered in order to deal with the consequences for the network capacity of added hydrogen. Examples of these options are:

1 Temporal reduction of hydrogen addition. Pipelines are usually not continuously loaded up to their full capacity and so, for most of the time, there will be spare capacity for the addition of hydrogen, without limiting the energy transmission and distribution capacity of the delivery system. In case the full capacity of a pipeline used for natural gas hydrogen mixtures is needed, for example on a very cold winter day, it may be necessary to decrease the percentage of hydrogen carried and, perhaps, to abort the delivery of hydrogen to some consumers. Of course, this option has to fit with the arrangements made with the connected end users as well as the producers of hydrogen .

2 Increase of the capacity of the transportation and distribution system by for instance the construction of additional pipelines and compressors. As end users need a certain amount of energy and as the addition of hydrogen will decrease the caloric value of the gas delivered, the flows will increase accordingly. Network companies are used to checking regularly the capacity of their system, and in case of a bottleneck there are measures in place to deal with this.. Generally speaking, an increase of the operating pressure is not appropriate, as the operating pressures of networks are already optimised on well-considered grounds.

It is favourable for all parties involved if plans for hydrogen addition in the natural gas network are discussed with the network company in a early stage of development in order to take the specific situation of the network capacity into account.

5 The NATURALHY project

5.1 Objectives

The main objectives of the NATURALHY project are:

- to define the conditions under which hydrogen (pure, or as a part of a mixture with other gases) can be added to natural gas in the existing natural gas system (transmission, distribution, end use, infrastructure and appliances) with regard to:
  - acceptable safety risks;
  - benefits;
  - impact on the integrity of the system;
  - consequences for gas quality management and for the end user.
- to develop technical options (particularly membranes) to separate hydrogen from hydrogen/natural gas mixtures;
- to assess the socio-economic and life cycle aspects of the NATURALHY approach, thus illustrating the real value of the NATURALHY project.

The main technical deliverable of the project will be an expert system, the “Decision Support Tool”, that will determine the maximum percentage of hydrogen that can be added to natural gas supplied in any given section of a natural gas pipeline system and identify the factors that limit the percentage.

It should be noted that although the objectives of the NATURALHY project concern hydrogen-natural gas mixtures, the outcomes are very relevant for defining the conditions under which the existing natural gas system can be used for biogas, hydrogen produced from syngas, and other sustainable produced gases containing a certain amount of hydrogen, including SNG. Moreover, the information gained in this project can be used to determine to which extent the existing pipeline network can be used for the delivery of pure hydrogen. In this specific case, changing the operational conditions, particularly the pressure regime, and some of the hardware (e.g. compressors) would seem to be a necessity.

5.2 The NATURALHY-programme

In order to meet the objectives mentioned in the previous paragraph, a set of coherent Work Packages, detailed below, have been defined within the NATURALHY project. The programme is further explained in Figure 4:

WP1 Life Cycle and Socio-economic Assessments comprises a comparison of the main natural resource requirements, environmental impacts, employment consequences and economic costs over the complete life cycle of current natural gas and related energy systems, proposed transitional natural gas/hydrogen systems, and future complete hydrogen systems from source to point of use.

WP2 Safety will enable the risks presented by the transmission, distribution and use of a hydrogen/natural gas mixture to be compared with those for natural gas. To ensure credibility amongst system operators, the major hazard scenarios previously studied for natural gas and pure hydrogen will be re-examined experimentally for hydrogen/natural gas mixtures. Tests will include investigation of explosions and build up of gas in confined/vented enclosures and congested regions, high pressure jet fires and pipeline fires. Large scale experimental testing is crucial to the NATURALHY project as fire and explosion phenomena are scale dependent. The results will be used to modify existing risk assessment methodologies, developed originally for natural gas. The modified risk assessment methodologies will then be used to undertake risk assessments to compare with those completed for the existing natural gas system.

WP3 Durability will determine the effects of hydrogen on the durability of materials and components used in the natural gas transmission and distribution networks and end user infrastructure. Existing defect assessment criteria will be adapted to take into account an increasing percentage of hydrogen in natural gas. The results will be processed to produce mathematical durability lifetime models. From these models, a durability assessment tool will be developed to assess the ageing of materials and components and to provide a practical way of evaluate the system lifetime given its characteristics and the percentage of hydrogen.

WP4 Integrity will assess the effectiveness of NDE (Non Destructive Evaluation) tools and techniques to monitor the condition of transmission and distribution pipeline systems exposed to natural gas/hydrogen mixtures, and of the maintenance and repair procedures for such pipeline systems. It will improve knowledge on realistic defects, on the methods to detect & assess them according to the defect assessment criteria relevant for natural gas/hydrogen atmospheres and to repair these defects. An integrity management tool will be developed.

WP5 End Use will examine the implications of providing distributed pipeline natural gas/hydrogen mixtures to end-users and the effect on existing appliances. A survey and analysis of existing data will be undertaken to assess the impact of added hydrogen on the performance characteristics of existing natural gas appliances including, domestic and industrial burners, particularly industrial burners used for glass industry. This will lead to an understanding of the requirements for existing and new appliances to operate safely and efficiently with increasing levels of hydrogen. A R&D programme is being conducted to develop high efficiency membranes and to provide options for separating hydrogen from the distributed hydrogen/natural gas stream for end-use applications at various scales. Methods for re-establishing the gas quality as hydrogen is progressively removed will be identified and assessed.

WP6 Decision Support Tool will develop an expert system to assess the suitability of an existing gas system (including transmission and distribution pipelines, end user appliances and operational aspects) to cope with whichever hydrogen/natural gas mixture is proposed. With this tool, NATURALHY deals with the fact that no general, simplistic figures on acceptable hydrogen percentages to be added to natural gas can be determined. As explained in paragraph 4.4, the determination of the suitability of a natural gas system for hydrogen must be made by a rigorous examination of the specific conditions pertaining.

WP7 Dissemination ensures that the results of the NATURALHY project are made available to targeted technical/scientific stakeholders and decision makers at various levels. It achieve this via a series of appropriate actions, including publications, workshops, technology transfer activities and regular interfaces with government bodies, safety authorities, standards bodies, consumer organisations, environmentalists, decision-makers at both national and European levels.

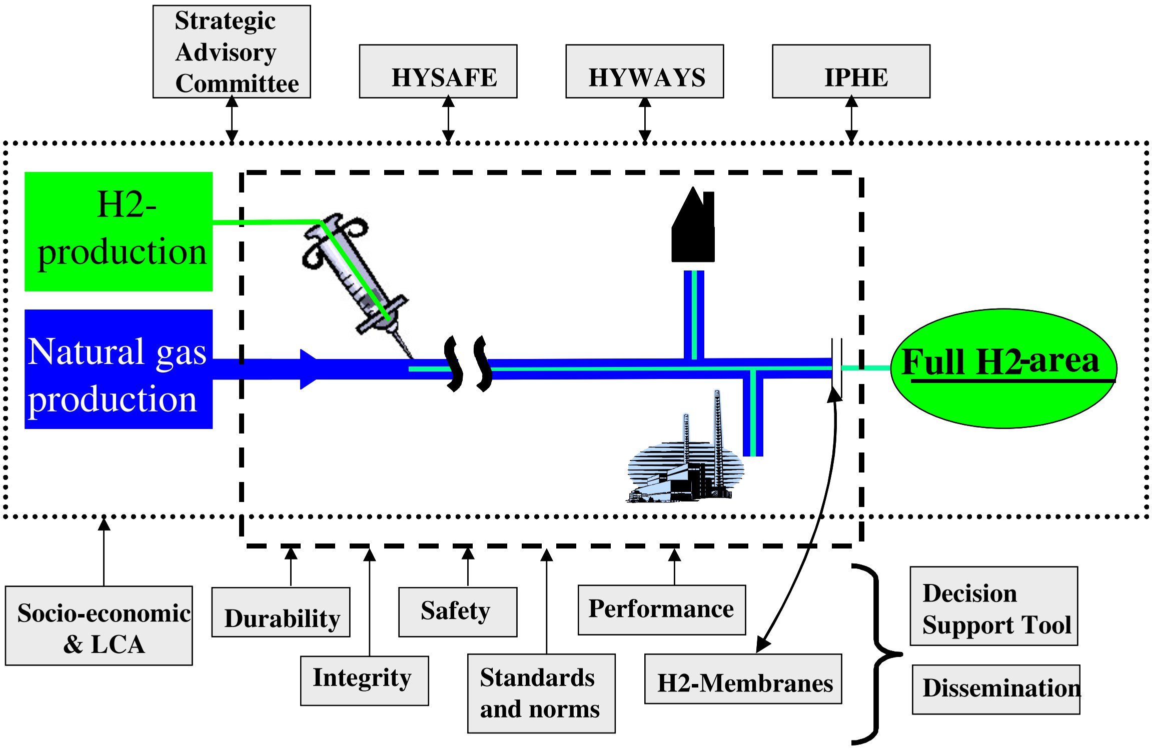

Figure 4: The main clusters of activities of the NATURALHY project and the other EC supported hydrogen projects with which collaborations exist

5.3 NATURALHY connected to the world

The communication with stakeholders and other on-going research projects is essential to ensure that:

- the NATURALHY project maintains an awareness of, and takes into account, developments in the fields relevant to the project;
- the NATURALHY results will find a broad acceptance;
- the NATURALHY results will establish a benchmark and, hence, be integrated into other research projects.

Therefore, as indicated in Figure 5, the following arrangements have been made in addition to the comprehensive dissemination programme explained in the previous paragraph:

- the NATURALHY Strategic Advisory Committee (SAC) has been established. This Committee addresses the strategic aspects of the project and establishes a platform for dissemination and for promoting public understanding and acceptance. It consists of the leading NATURALHY partners and representatives of organisations leading in the field of energy, natural gas, policy making, safety, environment, regulations/standards in relation to hydrogen. At the moment of preparing this paper the Committee includes amongst others the following organisations: IGU, IEA, Eon-Ruhrgas, European Hydrogen & Fuel Cell Technology Platform (HFP), ENItecnology, GERG – The European Gas Research Group, DVGW, IAHE, NaturCorp, CONTINUON, UK Health & Safety Executive, HYSAFE, HYWAYS, EU Commission, NL Ministry of Economics, EU-Parliament, US Department of Energy, CEN. This is a fluid organisation and discussions are continuing with several hydrogen producers regarding participation.

- The NATURALHY project collaborates\collaborated with the HYWAYS project (completed), the Network of Excellence HYSAFE, and the Roads2HyCom project (completed).
- The NATURALHY project has been recognised as a project in the International Partnership for the Hydrogen Economy, and aims at worldwide collaboration with other projects and organisations.

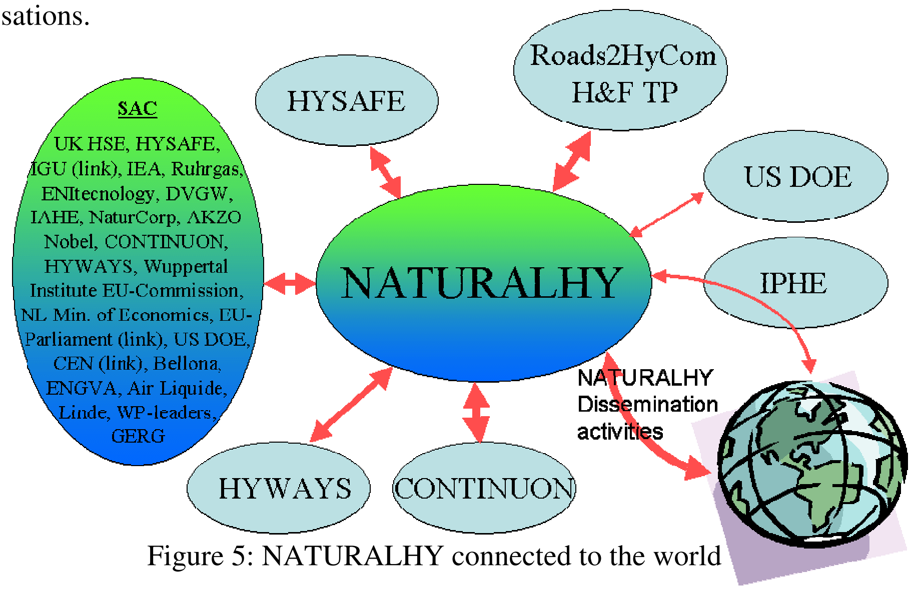

Figure 5: NATURALHY connected to the world

NATURALHY intends to enter into a collaboration with CONTINUON who will conduct a research programme on the suitability of PVC natural gas distribution pipelines for hydrogen/natural gas mixtures.

Finally, several NATURALHY partners participate in various national and international platforms, forums, working groups etc. in which NATURALHY results are introduced. In return, these partners also gather relevant information and views which are fed back into the project.

6 Related projects and recent studies concerning the co-transportation of hydrogen and natural gas

Since the inception of the NATURALHY project, the partners have maintained awareness of relevant on-going developments on hydrogen infrastructure throughout the world, since developments from these programmes will influence strategic planning in NATURALHY. While pursuing the objectives of the project, the intention is to ensure that NATURALHY remains aware and reactive to any new ideas and developments.

A number of strategic alliances have been forged to ensure that NATURALHY remains at the forefront of building towards a hydrogen infrastructure.

US DOE Hydrogen, Fuel Cells and Infrastructures Technologies Program. The DOE has a huge research and development programme on all aspects concerning the hydrogen chain, including an assessment of the potential of the existing natural gas infrastructure for hydrogen delivery. After a thorough assessment of the technical uncertainties and barriers, the approach of the DOE programme is oriented more towards basic research on materials and material degradation mechanisms, while in the NATURALHY project (in which there is a strong involvement of the natural gas industry) the scope is significantly broader and includes for instance safety, end user aspects, and Life Cycle and socio-economic Assessment.

In order to ensure that complementary subjects are investigated and that the exchange of results is satisfactory there is a frequent contact between NATURALHY and the DOE. In addition, DOE is represented in the NATURALHY Strategic Advisory Committee. The NATURALHY project coordinator and the leader of the Durability work package participate in the DOE Hydrogen Pipeline Group meetings. In the framework of the IPHE, an even stronger collaboration between the DOE Hydrogen Delivery Program and NATURALHY is foreseen.

In the framework of the IEA Hydrogen Implementation Agreement, recently a new Task has been proposed called “Large Scale Hydrogen Infrastructure and Mass Storage”. The envisaged working group dedicated to this new Task and NATURALHY have several parties in common, and NATURALHY will stay in close contact with this working group.

The project team is aware that in other parts of the world, notably Japan and Australia, work on specific aspects concerning the delivery and use of hydrogen/natural gas mixtures is being performed, However, to our knowledge, NATURALHY is the only project concerned with an integrated approach on all aspects of the transmission, distribution and end use.

7 Recent papers concerning hydrogen/natural gas delivery

In-depth studies on elements of the existing natural gas infrastructure for hydrogen/natural gas delivery are scarce. Outlined below is a selection of recent papers on the subject:

- On behalf of the IEA Greenhouse Gas R&D Programme, GASTEC prepared a report entitled “Reduction of CO_2 emissions by adding hydrogen to natural gas” (October 2003, Report PH4/24), in which the possibilities and consequences of the addition to hydrogen to natural gas are mapped out. In our opinion, the report does not show the needed transparency, contains significant inaccuracies and mistakes, and is not specific enough to have an impact on the NATURALHY programme.

- In March 2005 the report “Techno-economic assessment of hydrogen transmission & distribution systems in Europe in the medium and long term” (Report EUR 21586 EN) by P. Castello c.s. of the EC DG Joint Research Centre/Institute for Energy was issued. This report emphasises the relevance of hydrogen/natural gas mixtures in the existing natural gas networks. Although the parts on financial and environmental aspects are limited and there is some room for improvements of the gas transmission aspects, the report contains interesting data concerning economic aspects. With regard to technical issues, there is no real overlap with the NATURALHY programme and the report does not contain technical information that might have an impact on the NATURALHY program.

- In 2008 the Dutch EET project "Vergroening van gas" (Greening of gas) completed its programme. The project addressed among several other subjects, the issues of pipeline durability and end user aspects related to hydrogen/natural gas, topics that are also addressed in the NATURALHY project. The work in the EET project was complementary to the work of NATURALHY, and as some partners participated in both projects, results of EET were shared with NATURALHY.

8 Related projects and recent studies concerning the transportation of hydrogen

Although the basic aim of the studies and projects concerning infrastructure dedicated to hydrogen is completely different from the NATURALHY project, some aspects such as timescale, economics and LCA issues are relevant for comparison with the NATURALHY approach.

Concerning studies that are being carried out concerning the development of a new infrastructure dedicated to hydrogen from the evaluation of the existing industrial hydrogen pipelines the work of ECN should be mentioned (e.g. R. Smit c.s. "Modelling hydrogen infrastructure developments in the Netherlands", EHEC2005).

Some leading studies/projects concerning new hydrogen delivery infrastructures are listed below.

1. WE-NET (World Energy Network) Program is a project that has been conducted by the New Energy and Industrial Technology Development Organization (NEDO) since 1993 as part of the Japanese government's New Sunshine Program. The WE-NET Program aims to secure new energy sources and maintain the global environment in good condition by building an international network for hydrogen energy and concerns hydrogen production, transportation, storage and utilization systems.

2. The Hydrogen, Fuel Cells and Infrastructures Technologies Program of the US Department of Energy is focused on developing hydrogen delivery technologies that will enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power. Current research efforts are focused on:
   - hydrogen delivery research challenges at refuelling stations and stationary power sites. Research is being conducted to improve the reliability and lower the cost of hydrogen compression and to reduce the cost and footprint of hydrogen storage;
   - lowering the cost and energy use of the hydrogen delivery infrastructure. This includes developing improved lower cost materials for pipelines, breakthrough approaches to hydrogen liquefaction, lighter weight stronger materials and structures for high pressure hydrogen storage and transport, and novel low pressure solid and liquid carrier systems for hydrogen delivery and storage.

The Leighty Foundation promotes the introduction of hydrogen produced from renewable sources, and includes a plan for the construction of a windmill farm at the US Great Plains (North Dakota) and to supply the energy over a distance of 1500 km to Chicago. The transmission in the form of hydrogen turned out to be favourable to e.g. electrical transmission.