EXPERTS' ASSESSMENTS AND REPRESENTATIONS OF RISKS ASSOCIATED WITH HYDROGEN

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Abstract

Growing concerns about global warming, climate change, air pollution and the depletion of fossil fuels have prompted the search for better, environmentally friendly fuels capable of supplying the world economy in a sustainable way. Hydrogen is portrayed as the future "energy carrier" which will be capable of addressing all those issues better than current, traditional technologies based on hydrocarbon fuels.

Like any other technological system, one based on hydrogen will inevitably involve risks, associated with possible hazardous situations posing threats to safety, public health and the environment. To begin to understand how publics may develop, maintain and modify their attitudes towards a complex hydrogen-based system and its relative risks, it is necessary to address how those risks are currently represented in the scientific literature and communicated to the wider public.

By drawing on an extensive review of relevant literatures, the paper aims at exploring and eliciting the way in which prospective risks associated with hydrogen are assessed and variably represented by "the experts".

INTRODUCTION

According to the fast-growing scientific and popular literature, hydrogen, the most abundant and lightest element of the periodic table, will play a key role in the future energy economy. Growing concerns about global warming, climate change, air pollution and the depletion of fossil fuels have prompted the search for better, environmentally friendly fuels capable of supplying the world economy in a sustainable way. Hydrogen is portrayed as the future "energy carrier" which will be capable of addressing all those issues better than current, traditional technologies based on the exploitation of hydrocarbon fuels (Rifkin, 2002; Dunn, 2002). The advantages of adopting hydrogen as an energy vector lie in the possibility of eliminating pollution and greenhouse emissions at least at the point of use. In fact, when hydrogen is used in a fuel cell to produce electricity, it is combined with oxygen and the only by-product is water. This theoretically simple principle has been long known to scientists. However, practical applications of using hydrogen as a fuel have struggled to emerge, mainly because of great technical difficulties encountered in devising cost-effective ways of producing and storing hydrogen (Harris *et al.*, 2004), and releasing the energy it carries.

As an innovative and benign energy vector, hydrogen is advocated by very different lobby groups belonging to a diverse range of organisations, sometimes with contradictory missions. Examples include public and private research groups, think tanks, industrial companies and environmentalist groups. A comparably heterogeneous spectrum of motivations drives hydrogen stakeholders: security of supply in a world where fossil fuels, especially oil, are concentrated in or have to be piped through politically unstable areas; global warming concerns requiring a decisive reduction of man-generated greenhouse gases; poor air quality in urban and congested areas, with deleterious effects on public health; improved use of renewable sources of energy, since hydrogen would allow energy systems to cope with fluctuating renewable energy production; revival of nuclear energy as a possible emission-free way of producing hydrogen.

Prospective hydrogen applications will be substantially different from the past and present uses of hydrogen as an industrial commodity. New applications are centred on the use of hydrogen as an energy carrier, thus placing hydrogen at the core of a complex, yet-to-be-developed energy system. The energy stored in hydrogen would then be used within different technological systems[1] for a multiplicity of different end-uses, encompassing mobile, stationary and portable applications. From a consumer's point of view, hydrogen applications in the transportation sector perhaps provide the most interesting and visible example, with the development of hydrogen-powered fuel cell or internal combustion engine (ICE) vehicles. Stationary applications include combined heat and power (CHP) systems for distributed energy production and local consumption; hydrogen-based portable technologies comprise durable power for laptops, mobile phones and other high-tech electronic consumer products. Apart from this last type of use - where hydrogen would directly substitute either for electricity or for conventional energy storage technologies, such as batteries - mobile and stationary hydrogen applications would entail a gradual (to an as yet uncertain extent) displacement of hydrocarbon fuels, such as natural gas, petrol and liquefied petroleum gas (LPG).

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[1] Here "technological system" refers to a set of combined technologies which serve a specific purpose, such as transportation technologies or energy delivery technologies (Rosenberg, 1982).

Additionally, the present infrastructure built around fossil fuels would need to be adapted or replaced by new, hydrogen-dedicated storage and delivery systems comprising liquid, gaseous and solid storage technologies (breakthroughs are needed in this area, in particular low-cost materials with high energy density), pipelines, ground distribution fleets and fuelling facilities.

Like any other technological system, one based on hydrogen will inevitably involve risks, associated with possible hazardous situations posing threats to safety, public health and the environment. To begin to understand how publics may develop, maintain and modify their attitudes towards the complex hydrogen-based system and its relative risks, it is necessary to address how those risks are currently represented in the scientific literature and communicated to the wider public.

This paper draws upon an extensive review of relevant scientific and technical literature on hydrogen. A variety of sources have been analysed, comprising peer-reviewed journal papers, technical reports, specialised magazine articles and internet web sites. Techno-scientific literature varies in terms of scope and depth of analysis, giving rise to different levels of accessibility by non-scientists. The reviewed documents principally address technical aspects and performance of hydrogen and hydrogen-based technologies, thus being examples of the "technological characterisation" approach (Hodson *et al.*, 2004). The concept of technology characterisation, along with that of technology assessment, refers to a broad variety of approaches addressing technical performance and cost effectiveness of technologies, by drawing on highly specific, often non-contextualised, forms of scientific and economic knowledge.

The paper also aims at exploring and eliciting the way in which risks associated with hydrogen, concerning safety, public health and the environment, are represented and communicated by "the experts" to "lay" people. Experts are in general stakeholders with an in-depth knowledge of hydrogen and variably affiliated to research organisations, commercial companies, interest groups or government bodies linked to the development of the "hydrogen economy".

Hydrogen as an energy carrier is usually evaluated against the current spectrum of conventional energy carriers, such as natural gas, petrol and liquefied petroleum gas (LPG).

Methane is the principal component of natural gas, produced from gas wells and landfill gas or in conjunction with crude oil production and water and sewage treatment. Natural gas may be stored in gaseous compressed form (CNG) or liquefied form (LNG). Petrol is a blend of hydrocarbons, produced from petroleum through distillation and refining processes. Propane is the main component of liquefied petroleum gas (LPG), which is a by-product from natural gas processing and crude oil refining. As a fuel for mobile applications, propane has been used in light- and medium-duty vehicles over the past 60 years.

Several issues should be clarified from the start. *First*, it should be clear which of the possible meanings of risk is used throughout the paper. In fact, risk has been variably conceptualised within different disciplinary contexts, each leading to a particular definition, and across historical periods. Within the reviewed literature, risk is generally understood as "technological risk", which can be measured as the product of the probability of an event and the magnitude, or severity, of such event. *Second*, it should be clear how the concept of risk is related to hydrogen, as various, often contradictory, visions of the hydrogen economy have been developed to date. On a first and narrow level of analysis, the risks of hydrogen can merely be those arising from handling it, as hydrogen mixed with air becomes a combustible and explosive substance. However, risks can also be viewed in a broader perspective, by taking into account additional risks arising from the whole life cycle of hydrogen, from production, through storage and distribution, to its final use. In fact, since a future "hydrogen technological system" will be made up of several different technologies and will interrelate with other complementary technologies, risk issues will arise also from parts of the system other than hydrogen itself and from the complexity and vulnerability of such system. The nature, severity and mitigation of such risks will therefore be strongly dependent upon the technical configuration the hydrogen system will finally display, and the co-development of socio-technical knowledge and routines, such as standards and regulations.

A comprehensive technological risk assessment of hydrogen-based futures has not been attempted to date, but several projects carried out at international level are developing risk assessments of specific hydrogen-based technologies and facilities.

HYDROGEN AT A GLANCE

Before natural gas was introduced as a household commodity, hydrogen had been used for many years in some European countries, such as the U.K. and Norway, as the main component of “town gas”, a combustible gas derived from coal.

According to DOE (2004) hydrogen has been used for the past 50 years in large quantities as a feedstock for a wide variety of industrial applications. Ammonia production for fertiliser accounts for about two thirds of total commercial use of hydrogen as an industrial gas. Other examples include petroleum upgrading (hydrocracking, hydrodealkylation, and hydrodesulphurisation) for such products as reformulated gasoline; food processing, such as hydrogenation of fats and oils, in which vegetable oils are changed from liquids to solids; semiconductor processing; glass and steel manufacturing; cooling systems for large turbine generators. Because of the very low temperature at which is stored, liquid hydrogen is also used in the cryogenics industry and within the study of superconductivity. The only large-scale use of hydrogen as a fuel is that of NASA. Nowadays, hydrogen production amounts to 9 million tons per year in the US alone and to 50 million tons worldwide. Methane steam reforming is the most common and cheapest method to produce hydrogen, which is also obtained in smaller quantities through electrolysis of water and as a by-product of other processes. Estimates suggest that the United States use more than 90 billion cubic meters of hydrogen each year.

Almost all of the hydrogen used is “captive”, that is consumed at the refinery or chemical plant where it is produced. The remaining part is the so-called “merchant hydrogen”, which is produced to be sold to manufacturing companies worldwide. A limited distribution network, consisting of liquid hydrogen delivery trucks, gaseous hydrogen tube trailers and dedicated hydrogen pipelines has been developed over the years.

Currently, hydrogen-based energy technologies exist only in the form of prototypes or are still at the laboratory stage. The complex technological system that would sustain hydrogen production, storage, delivery and end-uses is still the subject of numerous, often contradictory, conjectures. Hydrogen as an energy carrier is thus at the heart of a newly emerging complex technological system, whose future pervasiveness and technical details are highly uncertain and difficult to predict. In this context, it becomes very challenging to assess potential benefits, costs and risks of this system as compared to those of the present fossil fuel economy.

Hydrogen is the lightest element of the periodic table and naturally occurs in molecular form (H_2) or in more complex molecules, mostly organic compounds. At ambient temperature and pressure (25 ºC, 1 atm) hydrogen is in gaseous form. It becomes liquid when it reaches its boiling point (-253 ºC). Normally, temperatures below –73 ºC are referred to as cryogenic, and fuels at those temperatures are commonly known as cryogenic fuels. Hydrogen, like methane and propane, is odourless, colourless and tasteless. Compounds such as mercaptans and thiophanes, usually added to scent natural gas, cannot be currently employed with hydrogen as their sulphur content may poison the fuel cell. Hydrogen is generally classified as non-toxic and non-carcinogenic.

Basic and generic information on chemicals, including hydrogen and traditional fuels, can be found in Material Safety Data Sheets, usually developed within occupational safety and health departments. By analysing and comparing those compiled within the International Programme on Chemical Safety (http://www.cdc.gov/niosh/ipcs/icstart.html), it emerges that, as for any other combustible material, the most important hazards associated with hydrogen are fire and explosions following unintentional leaks. Asphyxiation may be of concern if hydrogen concentration becomes high enough to displace oxygen. Moreover, cold burns may be caused by spills of liquid, cryogenic hydrogen.

Material safety data sheets, however, do not offer more detailed information on hydrogen properties and on the extent to which they differ from those of conventional fuels.

	Hydrogen	Methane	Propane	Petrol
Physical/ chemical dangers	The gas mixes well with air, explosive mixtures are easily formed. The gas is lighter than air. Heating may cause violent combustion or explosion. Reacts violently with air, oxygen, halogens and strong oxidants causing fire and explosion hazard. Metal catalysts, such as nickel and platinum, greatly enhance these reactions.	The gas is lighter than air	The gas is heavier than air and can travel along the ground. Distant ignition possible. Gas may accumulate in low ceiling spaces causing deficiency of oxygen. As a result of flow, agitation, etc., electrostatic charges can be generated.	The vapour is heavier than air and may travel along the ground. Distant ignition possible. The vapour mixes well with air, explosive mixtures are easily formed. As a result of flow, agitation, etc., electrostatic charges can be generated.
Fire hazard	Extremely flammable. Many reactions may cause fire or explosions.	Extremely flammable.	Extremely flammable.	Highly flammable.
Fire prevention	NO open flames, NO sparks, NO smoking	NO open flames, NO sparks, NO smoking	NO open flames, NO sparks, NO smoking	NO open flames, NO sparks, NO smoking
Explosion hazard	Gas/air mixtures are explosive.	Gas/air mixtures are explosive.	Gas/air mixtures are explosive.	Vapour/air mixtures are explosive.

	Hydrogen	**Methane**	**Propane**	**Petrol**
Explosion prevention	Closed system, ventilation, explosion-proof electrical equipment and lighting. Use non-sparking hand tools. Do not handle cylinders with oily hands.	Closed system, ventilation, explosion-proof electrical equipment and lighting. Use non-sparking hand tools.	Closed system, ventilation, explosion-proof electrical equipment and lighting. Prevent build-up of electrostatic charges (e.g. by grounding) if in liquid state. Use non-sparking hand tools.	Closed system, ventilation, explosion-proof electrical equipment and lighting. Prevent build-up of electrostatic charges (e.g. by grounding).
Inhalation hazards	Non toxic, simple asphyxiant.	Non toxic., simple asphyxiant.	May cause drowsiness, unconsciousness and effects to the central nervous system. Asphyxiant.	A harmful contamination of the air can be reached very quickly on evaporation at 20ºC. Causes confusion, cough, dizziness, drowsiness, dullness, headache.
Skin/eyes hazards	Serious frostbite on contact with liquid.	Frostbite on contact with liquid.	Frostbite.	May be absorbed through skin and eyes, causing irritation, redness, pain.
Ingestion hazard				Causes nausea and vomiting. Possibly carcinogenic to humans. May have effects on the central nervous system and liver.
Environmental hazards				Harmful to aquatic organisms.

SAFETY ISSUES

Near-term risks to safety are addressed by the available literature in greater detail and with more emphasis than other potential hazards, as they have an immediate, visible effect. Moreover, safety hazards are investigated and discussed principally in the context of hydrogen storage, transportation and final use, while less information is available regarding potential safety hazards of hydrogen production technologies (an example is provided in Janssen *et al.*, 2003).

When attempting to assess the relative risks that hydrogen handling poses to people's safety, most of the reviewed documents set out with a comparative analysis of its physical and chemical characteristics against those of conventional fossil fuels. In fact, potential hazards to safety of people and surrounding environment depend, on the one hand, upon the physical and chemical properties of hydrogen, which appear to be quite different from those of the fuels currently in use. On the other hand, the likelihood, magnitude and mitigation of risks to safety strongly depend upon the specific context and technological system in which hydrogen is produced, stored, delivered and finally used.

A recurring theme which emerges from the review is that widespread diffusion of hydrogen as an energy carrier would necessarily require that people use it with the same level of confidence and familiarity as its fossil fuel counterparts, such as natural gas and petrol. Hydrogen, however, is different from those conventional fuels in terms of physical and chemical characteristics (Nasa, 1997; Cadwaller and Herring, 1999; Lanz *et al.*, 2001; HSE, 2004), so that its behaviour in leakages, fires and explosions, and consequently prevention and mitigation procedures, are significantly different.

Hydrogen properties and implications for safety

The following table (Alcock *et al.*, 2001; Lanz *et al.*, 2001) summarises the main physical and chemical properties of hydrogen as compared to methane, propane and petrol. The numerical value of each property is confirmed across a variety of sources (Barbir, NASA, 1997; DOE, 2003).

Physical/Chemical characteristics	Hydrogen	Methane	Propane	Petrol
Heating value (kJ/g)				
Lower heating value (LHV)	119.93	50.02	45.6	44.5
Higher heating value (HHV)	141.86	55.53	50.36	47.5
Energy density at LHV (kJ/m^3)				
Gas at 1 atm and 15 ºC	10,050	32,650	86,670	na
Gas at 3,000 psig and 15 ºC	1,825,000	6,860,300	na	na
Gas at 10,000 psig and 15 ºC	4,500,000	na	na	na

Physical/Chemical characteristics	Hydrogen	Methane	Propane	Petrol
Liquid	8,491,000	20,920,400	23,488,800	31,150,000
Flammability limits (vol. % in air)				
Lower limit (LFL)	4	5.3	2.1	1
Upper limit (UFL)	75	15	9.5	7.8
Minimum ignition energy (mJ)	0.02	0.29	0.26	0.24
Min autoignition temperature (ºC)	585	540	487	228-471
Thermal energy radiated from flame to surrounding (% of total flame energy)	5-10	10-33	10-50	10-50
Quenching gap at NTP(mm)	0.6	2	2	2
Detonability limits (vol. % in air)				
Lower limit (LDL)	11-18	6.3	3.1	1.1
Upper limit (UDL)	59	13.5	7	3.3
Maximum burning velocity (m/s)	3.46	0.43	0.47	
Concentration at maximum (vol. %)	42.5	10.2	4.3	
Burning velocity at stoichiometric (m/s)	2.37	0.42	0.46	0.42
Concentration at stoichiometric (vol. %)	29.5	9.5	4.1	1.8

All the reviewed documents agree on some fundamental technical issues. With regard to risks to safety, unintentional hydrogen leaks are generally considered serious hazards, because hydrogen becomes combustible when mixed with air. In the presence of ignition sources, such as electric sparks, flames or high heat, hydrogen leaks can cause combustion in air, which in turn may generate an explosion in specific circumstances. In fact, most of the technical reports agree that the greatest potential risk to the public appears to be a slow leak in a confined space, such as a home garage, where accumulation of hydrogen may lead to fire and explosion if no detection systems or venting are in place. Hydrogen flames, moreover, are almost invisible in day light and emit less heat than other fuels, so that human senses alone are less able to detect them.

Liquid hydrogen entails other types of hazards to safety, given its cryogenic temperature (-253 ºC is the boiling temperature), such as severe frostbite. Hydrogen gas can be asphyxiant if released in large amounts, as it can displace oxygen.

Hydrogen embrittlement of metal and non-metallic materials, such as steel and plastics, is recognised as a potentially hazardous phenomenon. It consists of the penetration of hydrogen into the molecular structure the material. Consequently, it causes a severe loss of strength of the material and the possibility of catastrophic ruptures of hydrogen containment systems.

Having the smallest molecule of all substances, hydrogen has the greatest propensity to leak past seals and through tiny cracks. The leak rate is dependent on the kind of release, subsonic or sonic, as different physical properties come into play. If hydrogen is stored at high pressure, the flow from any leaks is likely to be sonic, so hydrogen would leak 2.8 times faster than natural gas and 5.1 times faster that propane on a volumetric basis. However, as hydrogen has a low energy density, the energy leakage rate would be 0.88 times smaller than methane and 0.61 than propane (Alcock *et al.*, 2001).

Being significantly lighter than air, hydrogen gas is more diffusive and buoyant than conventional hydrocarbon fuels, so it disperses more rapidly when released especially in open spaces. However, if cryogenic liquid hydrogen is released, the cold vapour cloud may initially be denser that the surrounding air. Buoyancy effects may be neglected at low concentration and high momentum releases, in which the orientation of the release can predict the direction of the cloud formation.

In contrast, spilled petrol pools in the vicinity of the leak resulting in a protracted fire and explosion hazard. Propane gas is denser than air and it slowly accumulates in low spots, whereas methane disperses rapidly, though not as quickly as hydrogen (Lanz *et al.*, 2001).

The wider flammability range and the lower minimum ignition energy of hydrogen raise safety concerns when compared with other fuels. The lower flammable limit (LFL), however, is similar to that of methane and higher than those of gasoline and propane. Most information sources agree that in many accidental situations the key parameter is the LFL, as ignition sources will ignite a fuel-air mixture as soon as a flammable concentration is reached. Moreover, the 4% limit is valid for upward propagating flames, while for downward propagating flames the LFL is 9-10%.

The ignition energy is dependent on the fuel-air concentration and reaches a minimum at around stoichiometric concentration (for hydrogen this is 29.5%). At the LFL the ignition energy for hydrogen and methane is almost the same. Moreover, weak ignition sources such as electrical equipment sparks, electrostatic sparks or sparks from striking objects involve more energy than is required to ignite all the fuels. A weak electrostatic spark from the human body releases about 10 mJ of energy, which is capable of setting fire to the majority of commonly used fuels.

To summarise, hydrogen might form a flammable mixture in closed spaces more readily than other fuels, due to its higher buoyancy, which in turn causes its ready dispersal in unconfined areas. The flammable hazard for hydrogen has a shorter duration than for other fuels. This does not apply to liquid cryogenic hydrogen. The particular way in which hydrogen combustion takes place has implications for safety. Hydrogen flames are invisible and hotter than hydrocarbon flames, and no smoke or soot is produced.

As already pointed out, hydrogen gas poses threats to personnel and to the public due to its combustibility and its potential for displacing oxygen in confined areas, such as: passenger compartment, boot, engine compartment in a vehicle; repair garage bay, tyre servicing bay, parking garage, residential garage, car wash building, etc. Explosion confinement areas could also be: a narrow street between tall buildings, tunnel, under a bridge, underground parking garage.

Uncertainties and knowledge gaps in the science become particularly evident when disastrous events involving hydrogen are considered, such as explosions with high-pressure gas. Limited experience of severe accidents has been accumulated so far, mainly within industrial settings, so that hydrogen's explosion behaviour following high-pressure releases and related likelihood of occurrence are currently poorly understood. To tackle this issue and to evaluate the comparative behaviour of hydrogen and hydrocarbon fuels on ignition, a number of tests and simulations have been independently conducted in the past (Swain *et al.*, 2003; Parsons Brinckerhoff Inc, 2004), while others are currently being executed (Dorofeev *et al.*, 2004) and planned (http://www.hysafe.org).

Following is a list of possible modes of hydrogen combustion (Cadwaller, Herring, 1999; Alcock *et al.*, 2001):

- *Diffusion flame*, like candle flame, can occur when H_2 leaks from a pressurised storage tank and does not mix well with air.
- *Flash fire* is a combustion event with little or no overpressure, where H_2 is not well mixed with air. It is a very rapid event, but burning velocity is at laminar value.
- *Deflagration explosions* can occur when the gas is well mixed with air (in the literature this is referred to as gas cloud release into the air or "pre-mixed system"). A deflagration is a combustion event where the combustion wave front is subsonic in the unreacted medium. The entire flammable range (4-75%) can support a deflagration. Normally, a deflagration is characterised by modest time scale and energy release. Overpressure theoretical maximum can be 8 times greater than initial pressure, but normally is less than that. Hydrogen has high flame speed (different from burning velocity). Deflagration explosions are less severe than detonations, however they raise safety concerns as even modest overpressures of a few psig and heat energy releases can harm people in the vicinity and can damage buildings, exposed equipment and the environment. Examples are debris, which can damage and cause secondary fires in the blast area. A complete combustion occurs when hydrogen is at stoichiometric concentration in air (29.5%), so this represents the worst scenario for calculating the maximum energy release in a deflagration. Normally, deflagration can occur at smaller concentrations, so the energy release will be lower.
- *Detonations* are combustion events where combustion wave front speed is supersonic. A detonation explosion may be the result of a transition from a deflagration. A detonation explosion is more severe than a deflagration explosion as the overpressures, or pressure waves, are higher (20 to 1 versus 8 to 1). Transition from deflagration to detonation (DDT) may occur, the propensity of which is proportional to the burning velocity. The range of concentration supporting a detonation is 18.3-59% in air. A detonation explosion is typically a fast time scale event characterised by high energy output, which requires a high energy ignition source of 10kJ or more. Direct detonation of a hydrogen cloud is less likely than a deflagration explosion as the ignition energy is in the 10 kJ range, the minimum concentration higher and detonable range narrower than the flammable range. Some gases (acetylene, gasoline vapours) have their deflagration-to-detonation limits at or much closer to the lower flammability limits. As for hydrogen, a deflagration can result in a detonation depending on hydrogen concentration, the degree of space confinement, the presence of obstacles or conditions that promote turbulence in the gas, and the strength of the ignition source. Weather conditions (humidity, wind) are also important factors. The overpressure blast can shatter windows, damage houses, knock a person down, but, according to Cadwaller and Herring (1999), it is not thought to be fatal or cause severe debilitating effects, such as ear drum rupture and lung damage. Most researchers agree that in an unconfined area a DDT is very unlikely. Some authors (Ciccarelli, 1998) have reported lower concentration limits for deflagrations to occur than 18.3% (about 11%) under specific conditions.

Flame propagation is also dependent upon the quenching gap, which is the largest passage that can prevent propagation of a flame when it is filled with a flammable fuel-air mixture. The quenching gap depends on gas composition, temperature pressure and passage geometry. The small quenching gap for hydrogen requires tighter tolerances, which makes equipment capable of containing hydrogen flames more difficult to build than equipment for hydrocarbon flames. According to Lanz *et al.* (2001) the quenching gap has no specific relevance for use with fuel cells, whereas this concept is useful to describe flame-extinguishing properties of fuels in internal combustion engines. Hord (1978) argues that experimental data indicate that a U-shaped enclosure plus the ground comprise sufficient confinement to support strong explosions in detonable hydrogen-air mixtures ignited by thermal ignition sources.

A preliminary conclusion from the available literature is that for hydrogen the most significant event in terms of safety is a deflagration. Hydrogen fires, in fact, are not regarded as a primary hazard. To prevent detonations in confined areas, such as vehicles, the design of pipes and closed components should take into account the physical dimensions that preclude flame propagation and, consequently, DDT.

When devising ways of employing hydrogen as a fuel for mobile applications, the likelihood of combustion events with hydrogen should be known. According to Cadwaller and Herring (1999), fire events are easier to quantify as they are dependent only on design characteristics and less on the weather conditions. Any detailed gas explosion analysis should include hydrogen physical state upon release, weather (humidity, wind, air temperature, etc.), obstacles or confinement, gas concentration and postulated ignition sources. A 5- or 8-kg mass fuel release into an enclosed location, such a vehicle or a residential garage would present a deflagration hazard and a potential DDT safety issue.

In sum, from the analysis of the literatures reviewed it is possible to highlight some of hydrogen's physical and chemical properties which have implications for safety, according to experts' assessments (also confirmed in DOE, 2004):

- density: hydrogen is the lightest of all elements;
- buoyancy: at room temperature, gaseous hydrogen has a very low density compared to air and other fuels. In the event of a leak from a container, it would rise more rapidly than methane, propane or gasoline vapour, and quickly disperse;
- diffusion: hydrogen diffuses through air more rapidly than other gaseous fuels;
- colour, odour, taste and toxicity: like methane and propane, hydrogen gas is colourless, odourless, tasteless and non-toxic;
- flammability and flame characteristics: flammability range is wider than conventional fuels, hydrogen burns with an almost invisible flame;
- ignition energy: lower than conventional fuels when concentration in air is neither lean nor rich;
- detonation limits: hydrogen is detonable over a wide range of concentrations when confined, however, unlike many other fuels, it is very difficult to detonate when unconfined;
- flame velocity: hydrogen has higher flame speed than other fuels when concentration in air is neither lean nor rich;

- auto-ignition temperature: compared to other fuels, hydrogen has a higher auto-ignition temperature (it requires higher temperatures to self-ignite);
- hydrogen embrittlement: hydrogen causes significant deterioration of materials, which may lead to leaks and catastrophic ruptures of hydrogen containers.

Experts' representations of safety risks associated with hydrogen

As reviewed in the present paper, experts and stakeholders provide varied approaches to interpret hydrogen's properties and assess its comparative safety, leading to differing and often contradictory results. This reflects, on one hand, the absence of a unique way to tackle this issue, on the other, the profound uncertainty which characterises early-stage hydrogen energy technologies. Hydrogen-based technologies, in particular in the transportation sector, are still being developed by major car manufacturers and, to a limited extent, tested in pilot projects involving prototype buses and vehicles. A dominant design is absent. In fact, various hydrogen storage methodologies and combustion techniques are currently under development. In the absence of an established frame of reference for hydrogen technologies, some authors focus on few hydrogen properties to deduce general statements about its comparative safety, others take into account a combination of those properties and attempt to draw conclusions valid in specific technical situations. In most cases, industrial experience with hydrogen is used to anticipate the nature of potential safety concerns arising from its use as an energy carrier and a vehicle fuel.

In a study funded by the National Hydrogen Association (discussed in Cadwaller and Herring, 1999), a qualitative assessment of the relative safety of hydrogen as compared to other fuels concluded that *hydrogen is more dangerous than methane and less dangerous than propane*. Tests showed, in fact, that when the three gases were released in a confined space, hydrogen was the quickest to form a flammable mixture. Moreover, hydrogen has the smallest ignition energy (0.02 mJ at stoichiometric concentration) of the three gases. In tests performed in vented spaces, however, the situation appeared reversed. Propane and methane yielded, respectively, a large and small flammable mixture, while hydrogen easily vented from the space and formed virtually no burnable mixture.

Significantly different conclusions are presented in Barbir (no date available), who analyses the possible consequences of unintended hydrogen leaks and compares them to those of conventional fossil fuels, by considering only the relative energy content of the fuels. It is argued, for example, that a *hydrogen leak would be less dangerous than a natural gas leak*. Analogously, it is claimed that a *hydrogen explosion would be less severe* than in the case of other fuels, as hydrogen has the lowest explosive energy per unit of energy stored in the fuel (22 times less explosive than petrol). When hydrogen is used a vehicle fuel, potential hazards come from the possibility of hydrogen fire and explosion in the fuel storage, supply lines or fuel cells. The author argues that the fuel cell poses the least hazard.

A study conducted by Directed Technologies, Inc. on behalf of Ford Motor Company (DTI, 1997) developed a risk assessment of several most probable or most severe hydrogen accident scenarios, namely fuel tank fire or explosion in unconfined spaces, fuel tank fire or explosion in tunnels, fuel line leaks in unconfined spaces, fuel leak in garage, and refuelling station accidents. The study concluded that in a collision in open spaces, a *hydrogen FC car would be safer* than either natural gas or petrol vehicle. In a tunnel collision, a hydrogen fuel cell car should be *nearly as safe as* a natural gas vehicle, both being *less dangerous* than petrol and LPG cars. The greatest potential risk to the public appears to be a slow leak in a confined home garage, where accumulation of hydrogen may lead to fire and explosion if no detection systems or venting are in place.

According to Lanz *et al.* (2001) "in many respects, *hydrogen fires are safer than gasoline fires*". "Hydrogen fires are vertical and highly localized. When a car hydrogen cylinder ruptures and is ignited, the fire burns away from the car and the interior typically does not get very hot." Conversely, "when a car gasoline tank ruptures and is ignited, the fire engulfs the car within the a matter of seconds and causes the temperature of the entire vehicle to rise dramatically." "Hydrogen emits non-toxic combustion products when burned. Gasoline fires generate toxic smoke". "All fuels are dangerous because they are highly chemical reactive. It is this reactivity that makes fuels excellent sources of energy. Hydrogen is not inherently more dangerous than other fuels, such as natural gas or gasoline, but its properties are unique and must be handled with appropriate care. *In many ways hydrogen is safer than other fuels*".

The European Hydrogen Integrated Project II provides the most up-to-date resources on safety issues concerning the use of hydrogen as a fuel. The project addresses the development of comprehensive safety standards and regulations for hydrogen. Several studies have been published which inform on the current knowledge base about the relative risks of hydrogen (http://www.eihp.org).

One of those studies consists of a comparative evaluation of fuel safety (Alcock *et al.*, 2001) aimed at collating existing safety data related to hydrogen and other conventional vehicle fuels. It analyses the physical and chemical properties of hydrogen to discuss their possible implications in terms of risks to safety. It is reported that past evaluations of hydrogen safety issues have neglected some important aspects of hydrogen combustion and explosion modalities, and focused only on the relative energy content of the fuel instead of addressing the differing behaviour of fuels on ignition. Moreover, it is argued that almost all past assessments have concentrated only on hydrogen onboard a vehicle and less on the safety issues of the entire fuelling infrastructure. However, this study does not offer detailed practical guidance on safety issues related to hydrogen energy systems. It is suggested that hydrogen safety should be addressed by taking into account several factors: the specific context in which an unintentional release of hydrogen may occur; the specific form of hydrogen being handled (liquid or gaseous); and its particular ignition and explosion modalities under those particular circumstances. These guidelines are focused on the local production, distribution and usage of hydrogen as a retail fuel. No risk issues are raised in the area of hydrogen large-scale production. The report by Alcock *et al.* (2001) concludes by stating that "the comparative safety of hydrogen can only be judged based on the particular circumstances in which it will be used. In some instances hydrogen's propensity to dissipate quickly, relatively high LFL and low energy density may make it a safer fuel than the alternatives considered. In other cases hydrogen's wide flammable range, small quenching gap and propensity to detonate may make it less safe."

Reports published within the EIHP II generally remark that "*the current knowledge about hydrogen safety is less thorough than the knowledge of safety of conventional fuels*", adding that knowledge gaps include a "general lack of data on frequency and size of hydrogen release" (EHIP II, 2002). As a consequence, various recommendations are made for gathering further experimental data on hydrogen leakage and combustion in confined spaces, such as tunnels and garages.

Analogous comments on the general need for more research and experimental studies on future hydrogen energy systems have recently emerged during the seminar "Hydrogen and the Public: Risk, Safety and Public Perception", held in London on December 3rd 2004 and organised by the environmental consultancy Cambrensis (http://www.cambrensis.org). In particular, Slater and Bowen (2004) criticised the current emphasis placed on the Hindenburg disaster, which occurred back in 1937. The general propensity of most experts to absolve hydrogen, they claim, is stifling the debate on safety and hindering the development of a balanced approach to hydrogen, regardless of the "real" cause of the accident. Bowen (2004) added that, as hydrogen is potentially a very hazardous fuel, it will require careful and responsible management in order for an untrained public to use it safely. He also identified several outstanding technical hazard quantification issues that need to be researched thoroughly: flame instabilities, turbulence, transition to detonation, mitigation strategies and quantification, mixtures, etc.

According to Dorofeev (2003), although numerous studies have addressed safety issues related to hydrogen, "no solutions are available in terms of widely accepted standards, methodologies, mitigation techniques, and regulations". Accumulated experience with hydrogen is presently limited to a number of industrial applications whose scale and proximity to the general public are small. Hydrogen is represented as a fuel with different properties from conventional fuels. In particular, he argues that hydrogen "is less dangerous in terms of thermal and fire hazards" but it "may be responsible for stronger pressure effects".

Potential hazards stemming from the use of hydrogen by the untrained general public are acknowledged by Dorofeev *et al.* (2004), who conducted various tests simulating explosions in partially vented, partially confined areas, such as the engine compartment, the passenger compartment, the boot or the vicinity of the vehicle. In particular, they determined the critical conditions for strong flame acceleration and deflagration to detonation transition. Flame acceleration is a measure of the capability of the combustion to become fast enough to result in a deflagration explosion, which in turn can lead to a detonation in certain critical conditions. The study points to the need for gathering more data describing unconfined explosions in congested areas, as these are much less understood than other cases though they represent realistic traffic situations.

Similar conclusions are expressed in the web site of a newly funded EU Network of Excellence (NOE) (http://www.hysafe.org/). The lack of a substantial amount of consistent data on hydrogen-related accidents, tests and simulations has so far prevented more detailed assessments of hydrogen safety in specific realistic conditions. Among other objectives, the Hysafe NOE will contribute to develop common understanding and approaches to address hydrogen safety issues, by creating and validating methodologies for safety assessment, undertaking safety and risk studies, promoting fundamental research and informing EU legal and regulatory decision makers with relevant project outcomes (Dorofeev, 2003).

Among the web sites, perhaps that of the U.S. Department of Energy, Energy Efficiency and Renewable Energy (http://www.eere.energy.gov/hydrogenandfuelcells), offers the most comprehensive background information on hydrogen safety and related issues. Although safety is not explicitly defined, publicly available documents affirm that "hydrogen has been used safely for decades by industry in a wide variety of applications and conditions, and it can be used safely by consumers with proper handling and engineering controls". "Hydrogen has a long history of safe use in the chemical and aerospace industries" as a consequence of applying "proper safety precautions and engineering controls, and established rules, regulations and standards". Hydrogen is regarded as safer than other conventional fuels, such as petrol, as it is non-toxic and dissipates quickly in case of a leak. "With proper handling and controls, *hydrogen can be as safe as, or safer than, other fuels that we use today*".

Similar statements are made in Doyle (1998), where it is suggested that hydrogen "is probably safer overall, provided some basic rules are followed". The lack of experience with hydrogen vehicles, however, is recognised: "the public was not involved, and all procedures were safely in the hands of qualified personnel".

In other DOE web pages and documents covering codes and standards, some problematic issues are highlighted, such as the limited safety data currently available for hydrogen systems and technological uncertainties affecting these systems. Like in the EIHP II reports, uncertainties and knowledge gaps emerge. In DOE (2003), Chapter 3.6, it is claimed that "*hydrogen is well known as a chemical, but its use as an energy carrier on a large-scale commercial basis is largely untested and undeveloped*".

In DOE (2003), Chapter 3.7, hydrogen is described as a "potentially dangerous substance because its low volumetric energy density requires high pressure and liquid storage", however it is argued that "its risk level at atmospheric pressure is similar to that of fuels such as natural gas or propane". The DOE document points to a number of challenges that need to be addressed to develop a comprehensive safety plan for hydrogen as a fuel. In particular, "the database of safety information on many hydrogen components and systems that would be used in a hydrogen infrastructure is limited to industrial practice". Moreover, the report refers to industrial secrecy issues as possible barriers to the diffusion of safety information on hydrogen, as "any new information may not be published because it is considered competition sensitive or proprietary". The lack of data adds to "a general lack of understanding of hydrogen and hydrogen system safety needs among local government officials, fire marshals, and the general public". However "there is no comprehensive Handbook of Best Management Practices for hydrogen safety" and many handbooks and training programmes on hydrogen safety may actually be "limited or inaccurate". It is also surprisingly acknowledged that "although hydrogen is listed as Class B hazard (defined as flammable and combustible material), some of the data used to classify hydrogen could not be reproduced in the DOE laboratories".

In sum, the barriers identified in DOE (2003) comprise:

- limited historical database for hydrogen components, so that "limited data are available on the operational and safety aspects of these technologies, and the materials from which they are fabricated";
- lack of access to industry proprietary data;
- need for validation of historical data related to safety parameters for the production, storage, transport, and utilisation of hydrogen, which are several decades old;
- incomplete understanding of the fundamental limits of hydrogen systems;
- limited knowledge on past hydrogen safety incidents, because in the U.S. there are no mandatory reporting requirements for these incidents.

Another document published by DOE (2004) presents hydrogen as "*neither more nor less inherently hazardous than gasoline, propane or methane*". It identifies several properties, which have implications with respect to safety as compared to conventional fuels. According to DOE (2004), prevention of leaks and undesired combustion of hydrogen is of paramount importance with respect to safety. Disadvantages are hydrogen's wide flammability limits and low minimum ignition energy. Both hydrogen and natural gas are less likely than propane and petrol to ignite in the case of a small leak in a closed area in the vicinity of an ignition source, as they have higher LFL. However, if hydrogen leakage is not interrupted and hydrogen accumulates, hydrogen will be more prone to be ignited by a distant ignition source than the other fuels due to its wider flammability range. As for explosions, the burning velocity of hydrogen-air mixtures is eight times as high as that of methane-air and propane-air mixtures. Burning velocity is an indication of the explosive potential of a combustible gas. In confined areas, hydrogen storage poses the hazards of combustion and explosion, however those hazards "can be addressed with proper design, engineering and operation".

In http://www.fuelcellstore.com/, safety information is presented by focusing on the similarities rather than the differences between hydrogen and conventional fuels. It is argued, for example, that hydrogen "possesses similar characteristics inherent to any of the fossil fuels commonly used by today's society". Moreover, hydrogen may be "actually safer" than conventional fossil fuels when "education and correct handling methods are applied".

In http://www.hydrogennow.org/ great emphasis is placed upon the explanation of the "real" causes of the Hindenburg disaster, which should then prove to the average public that future hydrogen-based applications can be enjoyed with "the same safety we have had with petroleum fuels". Again, hydrogen advantages with respect to safety risks are presented without discussing them in perspective and in relation to specific contexts. Examples include sentences of the type "hydrogen is less flammable than gasoline", "hydrogen disperses quickly", "hydrogen is a non-toxic, naturally occurring element", "hydrogen combustion produces only water", "hydrogen can be stored safely".

In http://www.hydrogensociety.net/, potential hazards related to hydrogen and relative mitigation mechanisms are briefly described. It emerges, as in other web sites, the confidence that non-industrial uses of hydrogen will enjoy the same degree of safety as past industrial experience.

The National Hydrogen Association (http://www.hydrogenus.org/) supports a more balanced view which affirms that "hydrogen is no more or less dangerous than other flammable fuels". It acknowledges that "all flammable fuels must be handled responsibly" and "hydrogen is flammable and can behave dangerously under specific conditions". As a consequence, hydrogen "can be handled safely when simple guidelines are observed and the user has an understanding of its behaviour".

According to the California Fuel Cell Partnership's web site (http://www.cfcp.org/), hydrogen is characterised by a "benign nature" and it "doesn't harm the environment or public health". In addition, it is claimed that "hydrogen already has been found to be as safe as other fuels we commonly use today", however evidence is not explicitly disclosed. A sense of trust emerges in the ability of the current petrol-based system and customers to adapt to the new fuel. Safety measures, the application of appropriate codes and standards, and adequate knowledge are identified as the key factors for a successful, safe commercialisation of hydrogen technologies.

In the EU-funded project Hynet web site (http://www.hynet.info), safety information is very coincise and points to the recurring view that proper handling and hazard prevention mechanisms will ensure safe operation of hydrogen-based systems.

According to IEA (1999) “there is no fundamental technical problem with transporting and using hydrogen”, however “it can be difficult to handle hydrogen and to store it safely and effectively”. The conclusion is that “in the opinion of many experts, it does not pose dangers greater than other fuels, merely different ones”.

Stakeholders have generally positive views of hydrogen (http://www.fuelcellsworks.com/). According to Joachim Wolf of German gas giant Linde, “hydrogen is totally safe” and may even be “safer than gasoline: hydrogen is not explosive, gas is explosive”. According to Christian Egenhofer, climate change policy expert and lecturer at University of Dundee, Scotland, safety concerns are not as pressing as environment and cost-effectiveness issues (Carstens, 2004).

Companies working in the field of hydrogen production or storage have similar positive attitudes to hydrogen as an energy carrier. On the Shell Hydrogen web site (http://www.shell.com/) it is argued that “hydrogen is neither more nor less inherently hazardous” than hydrocarbon fuels, so that accurate knowledge of its properties is sufficient to guarantee safe handling. Past experience in hydrogen industrial practice is regarded as an example of safe handling, from which it is possible to develop safe practices in non-industrial uses. Air Products, a hydrogen manufacturer, claims to have “an unsurpassed safety record in the safe production, storage, handling, and distribution of hydrogen” (http://www.airproducts.com/).

A recurring theme emerging from technical sources (DOE, 2004) and hydrogen-supporting web sites is that prospective safety hazards posed by hydrogen-based technologies can be addressed with the aid of proper design, engineering and operation; the development and application of appropriate standards and regulations; and the familiarisation of consumers through education and communication initiatives.

A study recently carried out by the U.S. National Academy of Sciences (2004) recognises that “experts differ markedly in their views of the safety of hydrogen in a consumer-centred transportation system”, although accumulated experience suggests “that hydrogen can be manufactured and used in professionally managed systems with acceptable safety”. In particular, it is claimed that a “salient and underexplored issue is that of leakage in enclosed structures, such as garages in homes and commercial establishments”.

To date, few opponents have raised their voice. Apart from expressing serious doubts about the economic and technological feasibility of a hydrogen-based economy, Shinnar (2003) also questions its safety characteristics, claiming that “*hydrogen is the most dangerous of all known fuels*” and hydrogen “cars would be a boon to terrorists”. Without disclosing his criterion, he ranks diesel as the safest vehicle fuel, followed by petrol, natural gas and propane. According to Shinnar, there is a contradictory attitude towards hydrogen with respect of other fuels. As an example, he recalls that small propane cylinders (explosive force between 40 to 100 lb of TNT) are not allowed to be transported through tunnels, whereas car companies propose hydrogen containers whose explosive force is 2-5 times as high as that of propane cylinders. “Gasoline is a reasonably safe fuel widely used” and “propane is far safer than hydrogen”. Hydrogen has numerous safety issues, concerning its propensity to leak, ignite and explode. He argues that current safety practices would forbid storage of large quantities of hydrogen as a measure to limit the maximum possible damage in case of an explosion. This would limit its commercial diffusion in populated areas. In disagreement with the majority of scientists who trust that careful design, regulation and operation will mitigate risks, Shinnar affirms that the "inherent risks in using hydrogen cannot all be avoided by developing safety standards or regulations". Moreover, he states that "devastating explosions" involving hydrogen have already occurred. He compares the risks of hydrogen as those imposed by nuclear power stations, although nuclear is, in his view, an option which society cannot abandon for the moment.

Less bitter criticism emerges from Cherry (2004), who is concerned that the "unspoken consensus" among the scientific community supporting hydrogen may cause important risk issues to be overlooked. He warns about the consequences for the development of a hydrogen future that such an uncritical approach may bring about. However, he acknowledges that hydrogen's potential benefits "are well known and convincing", making it "an attractive answer to a significant problem".

Romm (2004) doesn't oppose hydrogen development, however he calls for a more gradual introduction of hydrogen-based technologies and stresses the need for more basic research to solve technical difficulties of producing, storing, delivering and using hydrogen. He also warns about yet unsolved safety issues related to hydrogen as a fuel. The propensity of hydrogen to leak and catch fire, as well hydrogen embrittlement of materials, and risks of high-pressure ruptures are regarded as significant safety hazards.

Romm agrees with Moy (2003), who interprets the NASA-collected data on hydrogen safety records in a far different fashion from the general optimistic response. Those data (Nasa, 1997) show that 22% of industrial hydrogen accidents have been caused by undetected leaks, "despite the special training, operating procedures, protective clothing, and electronic flame and gas detectors". With this track record, Moy argues, "it is difficult to imagine how hydrogen risks can be managed acceptably by the general public". Moy in particular stresses the need to address liability costs of a future hydrogen economy, as undetected leaks, combustion and explosions would necessarily raise these issues.

RISKS TO HEALTH AND THE ENVIRONMENT

As risks to public health are concerned, all sources agree that hydrogen is non-toxic and non-carcinogenic, thus it does not present any concern for medium- or long-term health implications (HSE, 2004). If hydrogen substituted for hydrocarbon fuels in the energy and transportation sectors – which currently are responsible for most of the air pollution – no noxious gases and fumes would be emitted at the point of use, thus improving air quality and, consequently, public health.

However, focusing only on end-of-pipe emissions gives but one part of the whole picture, especially if risks to the environment are also accounted for. In fact, as hydrogen needs to be produced by using an energy source, its potential beneficial effects to the environment at the point of use may be cancelled by harmful emissions at the production stage. For example, according to the U.S. Department of Energy (reported in Wald, 2003), a fuel cell car powered by hydrogen produced via electrolysis (through ordinary electricity from the grid) would increase CO_2 emissions by 17%, compared to a conventional petrol–powered car. Sustainable hydrogen production and effective measures for reducing or eliminating greenhouse gas emissions (for example carbon storage and sequestration) should therefore be put into practice.

Comprehensive assessments of health and environmental risks should take into account the whole technological system of which hydrogen will be part, as well as the entire life-cycle of such system. This type of approach is commonly referred to as “well-to-wheel” or “cradle-to-grave” analysis and is broadly regulated by the International Organisation for Standardization (ISO, 1997). A wide array of established and new technologies will in fact contribute to the production, storage, distribution and use of hydrogen. The complexity of such a system, combined with the uncertainty characterising its future unfolding, does not allow easy predictions over the most appropriate sustainable pathway to producing and using hydrogen (McLellan *et al*, no date available). Storage materials, such as metal hydrides and carbon nanotubes, and various types of fuel cells components (such as electrolytes and catalysts) will be deployed across the hydrogen energy chain, in amounts which will depend upon the scale of hydrogen penetration in the economy and the relative adoption rates of different hydrogen technologies (based, for example, on different fuel cell types). Increased production, diffusion and disposal of such materials, some of which may be totally newly engineered, may have risk implications on public health and the environment.

An example of life cycle assessment (LCA) applied to polymer electrolyte membrane (PEM) fuel cells is provided by Pehnt (2001), who investigates the ecological impacts of the entire life cycle of the PEM fuel cell system according to ISO (1997). PEM fuel cells are becoming particularly important because of their modular structure, which allows considerable flexibility in portable, mobile and stationary energy applications. They can in fact be used in different power ranges by simply adding more stacks together. Car manufacturers are placing great expectations on PEM fuel cells as energy converters in future hydrogen-fuelled vehicles. The LCA carried out by Pehnt aims to determine the relative importance, in terms of ecological impact, of the stack production phase compared to that of the stack utilisation. It is concluded that the most significant environmental impacts of PEM fuel cells production are caused by the platinum group metals (PGM) materials used to fabricate the catalyst, followed by the materials and energy required to manufacture the graphitic flow field plates, which allows the feed of the fuel and oxidant and conducts the electricity generated in the fuel cell. Recycling and the use of clean primary energy sources are considered major requirements to achieve lower global warming emissions during both manufacture and utilisation of PEM fuel cells.

Analysing alternative routes of hydrogen production is of fundamental importance to identify and assess possible long-term risks to public health and the environment. Koroneos *et al* (2004) have recently applied the LCA approach to determine and compare the environmental impacts of six different primary energy sources which can be used to produce liquid hydrogen via electrolysis. In their study, they examine four categories of impacts having adverse consequences for health and the environment: greenhouse gas emissions, acidification[2] emissions, eutrophication[3] air emissions and winter smog effect emissions (solid particulate matter, SO_2, etc.). The worst environmental performance is achieved through the use of photovoltaic energy, due to the negative impacts of the manufacturing process of photovoltaic modules and their low overall efficiency. Steam reforming of natural gas and biomass also produce high negative effects. The best choices among those investigated appear to be wind, hydropower and solar thermal energy.

Some recent debates have focused on the possible risks to the environment posed by unexpected hydrogen leakages in a future pervasive hydrogen-based economy. Long-term risks to health have attracted comparably less attention.

With respect to health implications, Cherry (2004) outlines the possible consequences of a widespread use of hydrogen-based technologies, such as fuel cells and hydrogen storage systems. Catalysts are essential components of fuel cells, which accelerate the rate of chemical reactions involving hydrogen, and are usually made of mixtures of exotic metals, whose side effects in case of unintentional fires or during their disposal may raise safety, health and environmental concerns. Cherry provides past examples of hazards linked to new technology adoption, such as nickel-cadmium and lead-acid batteries, asbestos insulation, and lead-based paint. An additional new hazard for consumers would be the spontaneous large heat generation (pyrophoricity) of some catalysts used in fuel reformers when they are exposed to air. Various metal alloys are also being evaluated as possible storage medium in hydrogen cars, as metal hydrides. According to current technological knowledge, about 50-100 kg of metal would be required in a single car, thus posing significant challenges to safety, health and the environment. Cherry also addresses possible negative impacts to the environment caused by an increased usage of private transport, as a clean fuel option would possibly relax public commitment to energy saving and hinder institutional efforts to reduce energy consumption and traffic congestion.

Health hazards from components of fuel cells, such as the electrolyte and the membrane, are also mentioned in Gaston *et al.* (2001). A common electrolyte used in alkaline fuel cells is potassium hydroxide, which is known as harmful for all human tissue as it causes serious chemical burns. Sulphuric acid is corrosive and can oxidise certain materials. When burning it emits toxic fumes. The membrane used in Polymer Electrolyte Membrane (PEM) fuel cells contains fluorine, a substance that produces corrosive, toxic compounds when accidentally heated or set on fire. Lithium salts, present in Molten Carbonate (MC) fuel cells, do not pose toxicity dangers unless involved in a fire, when they produce toxic fumes.

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[2] Acidification is the process whereby air pollution – mainly ammonia, sulphur dioxide and nitrogen oxides – is converted into acid substances. Through the formation of "acid rain", significant damage affects forests, lakes, coastal ecosystems and ancient monuments (http://www.eea.eu.int)

[3] Excessive enrichment of water and soil with nutrients – nitrogen and phosphorus – that causes undesirable effects on ecosystems.

A recent study (Raugei *et al.*, 2005), performing a multi-criteria life cycle assessment of molten carbonate fuel cells against conventional natural gas turbines, highlights the difficulty of developing an all-encompassing picture of health and environmental implications of relatively new technologies, such as Molten Carbonate fuel cells (MCFCs). In fact, due to the prototype stage of this technology, "no established procedures are yet in existence for the decommissioning or recycling of the advanced ceramic materials employed in the fuel cell stacks". As end-of-life processes of components of MCFCs could not be included in the overall analysis, the authors warn that "a certain degree of uncertainty remains, especially with respect to the possible local impact caused by the inherent toxicity of Ni and Cr compounds". Therefore, they conclude that "further investigation in this field is required, especially in the case of MCFC, where toxic and comparatively rare metals are employed".

The impact of a widespread, large use of hydrogen on the environment has been acknowledged by the International Panel on Climate Change, whose Third Assessment Report (IPCC, 2001) points out that H_2 can negatively interfere with the atmospheric chemistry responsible for abating methane and other major greenhouse gases, although it does not consider molecular hydrogen a direct greenhouse gas. It clearly states that "in a possible fuel-cell economy, future (hydrogen) emissions may need to be considered as a potential climate perturbation".

Molecular hydrogen is the simplest trace gas species in the atmosphere, produced by both natural and man-made sources. Hydrogen is present in the atmosphere at about 500 ppb (parts per billion) as a mole fraction. According to the IPCC Third Assessment Report, the total amount, or budget, of a trace gas is the result of a complex interplay of its global source, global sink (responsible for gas consumption) and atmospheric burden. The largest sources of hydrogen are direct emission into the atmosphere and atmospheric oxidation of methane and isoprene. The largest direct emission sources of atmospheric hydrogen are motor vehicle exhausts (due to incomplete combustion of fossil fuels) and biomass burning, followed by atmospheric chemistry processes (methane and isoprene oxidation). The hydrogen global sink comprises two major factors: the soil, where microbes metabolise hydrogen to produce energy, and photochemical atmospheric reactions involving the radical OH. According to IPCC (2001), also confirmed by recent experimental discoveries (Rahn *et al.*, 2003), the current hydrogen budget is dominated by soil uptake, which accounts for the depletion of about two thirds of the total hydrogen burden.

Recently, environmental implications of a fully-fledged hydrogen economy have been at the centre of an interesting dispute hosted by the scientific journal *Science*. A research group in atmospheric science at the California Institute of Technology published a paper (Tromp *et al.*, 2003) where they predict dramatic consequences of unintentional leaks of hydrogen effects on the stratosphere, the upper layer of the atmosphere situated between 10 to 50 km above the earth surface. In synthesis, by basing on a computer simulation of atmospheric chemistry, Tromp *et al.* argue that unintended emissions of molecular hydrogen can have deleterious effects on the climate, including enhancing global warming and jeopardising the ozone layer. In their words, such consequences may include "stratospheric cooling, enhancement of the heterogeneous chemistry that destroys ozone, an increase in noctilucent clouds, and changes in tropospheric chemistry and atmosphere-biosphere interactions". Their predictions, however, are strongly dependent upon a number of assumptions based on guesses and uncertain scientific knowledge.

In particular, Tromp *et al.* (2003) base their conclusions on the following assumptions: hydrogen-based technologies will replace all current fossil fuel-based technologies; 10 to 20% of hydrogen would be released into the atmosphere due to unintentional leaks. This means that 60 to 120 trillion grams of anthropogenic hydrogen would be released into the atmosphere each year, which is about 4 to 8 times current emissions (estimates vary between 5 to 25 Tg/yr). They recognise relevant gaps in the science base, in fact state that "the current budget of H_2 is poorly known" and that mechanisms and variations of soil uptake of hydrogen, possibly the dominant player in hydrogen removal, "are poorly understood, and it is unclear how the global rate of uptake would respond to an increased flux of H_2 to the atmosphere". Thus they acknowledge that the overall biosphere response to increased anthropogenic H_2 emissions may well accommodate them, with no negative impacts on the ozone layer and atmospheric chemistry. In fact, describing their results, they speak about "unknown environmental impacts" rather that certain, assured threats.

The paper received strong criticism, mostly directed at the assumed leakage rates of 10-20%, which in the authors' opinion "should be expected". Kammen and Lipman (2003), Lovins (2003) and Lehman (2003) claim that those assumptions are overly pessimistic and unrealistic, and suggest reasonable expected leaks of 1 to 3%, for gaseous and liquid hydrogen delivery respectively. Instead of a total substitution of fossil fuels with hydrogen, they envisage a less pervasive and gradual diffusion of fuel cells into the economy.

Schultz *et al.* (2003) attempted to provide quantitative estimates of the impact of a hydrogen-based economy, by assuming that 50% of the current fossil fuel combustion would be replaced by hydrogen technology and hydrogen would be produced from renewable resources and nuclear energy. Their study, based on a model simulation of the tropospheric air chemistry, concludes that "a large-scale transition from fossil fuel combustion to hydrogen fuel cell technology can lead to substantially improved air quality and reduced climate forcing". Although these claims reject previous results (obtained by Tromp *et al.*) on possible serious consequences of increase in the tropospheric abundance of hydrogen due to leakages, they acknowledge some general challenges facing scientists who try to assess the implications of a hydrogen economy on the world climate. The authors in fact point out the uncertainties affecting key parameters used as inputs in modelling future scenarios, such as the current hydrogen budget and the composition of the future hydrogen technological system. In particular, the study claims that "the most critical parameters with respect to the atmospheric implications of large-scale hydrogen use appear to be the associated changes in methane and NO_x emissions. The possible reduction in NO_x emissions would lead to reduced tropospheric ozone (which is considered a powerful greenhouse gas) formation but also to a substantial degradation of the atmospheric oxidising power, which could further aggravate climate forcing caused by methane and other greenhouse gases." The paper also stresses that it is very difficult to give an estimate of the average leak rate in a full-scale hydrogen economy. Past and current experience suggest values between 0.1 and 3%. Leak rates of 10-20% are possible, but considered very unlikely to occur. Increasing concentrations of hydrogen in the atmosphere could also lead to stratospheric ozone depletion, however the extent of this phenomenon would not be dramatic: to a doubling of hydrogen concentration, obtained by assuming an extreme 10% leak rate, would correspond a 2% ozone depletion. This is contended also by the critical study of Tromp *et al.* (2003). The study warns about possible negative impacts of generating hydrogen without a contextual reduction of greenhouse gas emissions, as this could lead to increased climate forcing.

Another study (Prather, 2003) urges a more committed effort to evaluating possible environmental disadvantages of a hydrogen economy, by highlighting the need for more precise parameters related to the leak rates, atmospheric impact and changes in emission from the transportation sector. In his study, however, he questions the validity of Tromp *et al* conclusions, suggesting that their calculations lead to wrong estimates for H_2 abundance increase.

Further contributions to the debate about possible environmental impacts of a hydrogen-driven economy are presented in Derwent (2004). The paper estimates that if hydrogen completely replaced the current fossil fuel-based economy, a 1% hydrogen leakage would give 0.6% climate impact of actual fossil fuel systems. The global warming consequences of the global hydrogen economy will depend on the leakage rates for hydrogen manufacture, storage and distribution systems.

Analysing the dispute over the environmental implications of a hydrogen economy reveals, amongst other issues, underlying uncertainties in the science. These uncertainties affect not only the values of key parameters, but also the extent to which important processes, occurring in the atmosphere and responsible for the global hydrogen budget, are known and modelled. The atmosphere is in fact a complex mixture of various gases, including hydrogen, each playing a different role in the overall chemical processes which determine global climate conditions and rule interactions between the atmosphere and the biosphere. Most papers acknowledge a substantial lack of understanding of those processes, combined with poorly known, inaccurate data.

CONCLUSIONS

In relation to safety, expert knowledge is limited to industrial practices and tests with prototype hydrogen systems, mainly developed for small-scale mobile applications. Hydrogen's physical and chemical properties with implications to safety are generally agreed upon. However, experts provide various, sometimes diverging, interpretations of those data and offer different approaches to assess the relative safety of hydrogen as compared to conventional fossil fuels.

Analysis of the literature reveals that past and current industrial experience with hydrogen should be acknowledged but it cannot fully inform a comprehensive assessment of risks to safety associated with substantially different uses of hydrogen as an energy vector.

Knowledge gaps become particularly evident when possible long-term risks to public health and the environment are considered. Partly this is due to the difficulty of predicting the technical details and pervasiveness of prospective hydrogen-based technologies. In fact longer term risks to health may emerge from components of hydrogen-based technologies, rather than hydrogen itself.

The environmental implications of a future hydrogen economy have recently been disputed. Hydrogen is not a greenhouse gas itself, but may cause indirect greenhouse effects if released in large amounts in the atmosphere, by affecting the chemistry that rules the overall cycle and budgets of greenhouse gases. Several papers, based on rather different assumptions, have addressed this issue reaching quite contradictory results. The early-stage level of development of hydrogen technologies, combined with significant statistical and structural uncertainties embedded in atmospheric science, make predictions of this kind a rather difficult enterprise.

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