‘HYDROGEN: TOO DANGEROUS TO BASE OUR FUTURE UPON?’

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Growing concerns about global warming, air pollution, the depletion of fossil fuels and geopolitical fears regarding their future availability are driving massive investment in the search to meet the future energy needs of the world economy in a sustainable and environmentally friendly way. Hydrogen based technologies have been identified by many countries, multi-national companies and institutions as a major “energy carrier” in their multi-strand future energy scenarios. Hydrogen, however, is a dangerous substance[2] and some commentators express the view that this highly flammable gas is too hazardous to form a significant element of our future energy policy.

In common with other technological systems, those based on hydrogen will inevitably involve risks associated with possible hazardous situations posing threats to safety, public health or the environment. This paper objectively reviews the key hazardous properties of hydrogen and compares them with those of current fuels in common usage by drawing on an extensive review of relevant literatures. It then illustrates the way in which prospective risks associated with hydrogen are currently assessed and represented by various experts and communicated to the wider public. The picture emerging from this review is an inconsistent one, where uncertainties and knowledge gaps abound, despite an overall “unspoken consensus” on hydrogen.

The paper proceeds to explore how the issue of risk perception, as conceptualised within the sociology of risk, relates to the development of hydrogen as the fuel of the future. According to the latest published studies, public awareness and risk perception of hydrogen energy have received comparably less attention than other emergent technologies, such as biotechnology or nanotechnology. The paper discusses the various factors that may affect and mediate public attitudes to hydrogen-based technologies and considers how the balance of benefits, costs and risks may change in the medium term, by building on insights from relevant perception studies and recent fieldwork conducted by the authors with stakeholders and members of the public in the UK.

INTRODUCTION

Prospective 21st century uses of hydrogen will differ substantially from its traditional role as an industrial process chemical and commodity. These new applications will be centred

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[2] Dangerous Substances and Explosive Atmospheres Regulations 2002.

primarily on the use of hydrogen as an energy carrier, placing hydrogen at the core of a multifaceted energy system. The energy stored in hydrogen would be used within different technological systems[3] for a multiplicity of different end-uses, encompassing mobile, stationary and portable applications. From a medium-term future consumer's point of view, hydrogen applications in the transportation sector are perhaps the most important, as the development of affordable, practical hydrogen powered private vehicles appears to carry much of the responsibility for the continuation of at-will personal travel for ordinary citizens.

Stationary applications of hydrogen fuel cell (FC) technologies are also expected to be very important, especially combined heat and power (CHP) systems producing both thermal and electrical energy for in-house and local consumption. It is also highly probable that hydrogen-based portable technologies such as durable power for laptops, mobile phones and other high-tech electronic consumer products will compete effectively with battery-based systems.

The development and deployment of hydrogen economy devices is as difficult to predict as it is technically exciting. Hydrogen has been identified by many countries, multi-national companies and international organisations and institutions as a major "energy carrier" in their multi-strand future energy scenarios, supported by enthusiastic, optimistic visions (Rifkin, 2002; Dunn, 2002). On the other hand, hydrogen is one of those rare technological advances that does not enable the user to do anything new. All the currently conceived applications are designed to allow us to maintain our current lifestyle expectations against a backdrop of declining fossil fuel availability/affordability.

The distinctive advantages of adopting hydrogen as an energy vector as compared with using fossil fuels lie in the possibility of eliminating pollution and greenhouse emissions – at least at the point of use. 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 known to scientists for 150 years, but practical applications using hydrogen as a fuel have struggled to emerge, mainly because of technical difficulties encountered in devising cost-effective ways of producing and storing hydrogen (Harris *et al.*, 2004), and releasing the energy it carries. Moreover, hydrogen is classified a dangerous substance (Dangerous Substances and Explosive Atmospheres Regulations 2002) and some commentators express the view that this highly flammable gas is too hazardous to form a significant element of our future energy policy.

Hydrogen might (or might not) be too dangerous to base our future upon from any or all of three points of view:

1. Its properties as a hazardous substance, especially when applied in the ways currently envisaged;
2. Its representation in communication between 'experts' and the public;

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[3] 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).

3. How the public (or publics) perceive the risks, benefits and costs associated with using hydrogen as a substitute for the fossil fuels with which they are familiar.

In what follows, we shall consider each of these in turn.

THE HAZARDS OF HYDROGEN AS AN ENERGY CARRIER

In today's world, whenever a new technology is considered, concerns about the attendant risk of harm tend to share the stage with its opportunities and advantages. In this section of the paper, we seek to assess what is best available evidence and what is uncertain and relatively under-researched about the properties of hydrogen that might make it a hazard under certain conditions of use.

A diverse range of industry has used hydrogen for over 50 years and most commentators would probably agree that for the majority of this time the frequency of incidents associated with its use has been tolerably low. Is this because hydrogen is relatively benign? There are certainly those who promulgate the view that hydrogen is not particularly hazardous and, for example, did not play a significant supporting role in the Hindenburg tragedy (Bain and Van Vorst, 1999). Conversely, when taken at face value, an objective review of the frequently cited "headline" properties of hydrogen would appear to support the fearsome reputation which is promoted for this fuel in some quarters.

The breadth of opinion on the safety of hydrogen has prompted some to produce comparative ratings on the safety of hydrogen relative to other fuels in common use. A key driver for this work is frequently a presumption that the user population must be able to use hydrogen-based technologies with at least the same level of confidence and tolerable risk of harm that they currently routinely enjoy with established energy sources. Whilst this is undoubtedly the only acceptable basis at the current time, it is interesting, if somewhat heretical, to speculate how our concept of risk tolerability for hydrogen and other new or resurrected technologies will change as the declining availability/affordability of traditional energy sources increasingly threaten our lifestyle expectations. In situations such as these, it is considered highly probable that the public's demand for the application of the risk v benefit equation will start to apply increasing pressure on the regulatory mantra of ALARP (As Low As Reasonably Practical)[4].

Despite our contention that in twenty years time the benefit side of the risk v benefit equation will start to be given increased weight in the minds of ordinary citizens, we believe that it is valuable to revisit the important hazardous properties of hydrogen, to comment on their implications and to attempt to place them in context with the hazards accompanying the use of those fuels currently in routine use. The evidence from this comparison may then be used as a basis for projecting the likelihood that hydrogen may be capable of use in similarly challenging environments to those in which current fuels are used and with a similarly tolerable risk profile.

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[4] For the Health and Safety Executive's guidance to its own staff about ALARP, see http://www.hse.gov.uk/risk/theory/alarp.htm.

Hydrogen, a gas that does not liquefy until cooled to below −253°C at atmospheric pressure, is the lightest element of the periodic table. In common with methane and propane, it is odourless, colourless and tasteless and although non-toxic and non-carcinogenic can act as an asphyxiant. With regard to the present discussion, however, the more important hazards of hydrogen are its ready flammability, a frequently invisible, high temperature flame and its eagerness to burn or form explosive mixtures with air. Appendix 1 summarises several aspects of the combustion of hydrogen in air and provides comparison with corresponding data for methane, propane and petrol.

The very wide range of concentrations over which hydrogen/air mixtures are flammable is widely known and frequently used as the basis from which to argue that hydrogen is more dangerous than current fuels such as petrol, natural gas and LPG. Consideration should, however, be given to whether hydrogen's wider flammable range automatically translates into presenting a greater risk of harm in realistic incident scenarios.

Further consideration would seem to support the conclusion that only in those rare situations where an ignition source only becomes incendive *after* the fuel/air mixture is well established around it should the extent of the flammable range have a significant effect in increasing the likelihood that ignition would occur and consequently support the argument that increased flammable range equates to increased hazard and risk of harm.

The lower flammable limit (LFL) for hydrogen is similar to that of methane and higher than those of petrol or propane. This would appear to be potentially of great significance as there is considerable agreement amongst commentators that in many potential accident situations, the LFL is the key parameter rather than the extent of the flammable range. Ignition of the fuel/air mixture produced following a leak occurs when the front of the flammable cloud reaches the ignition source. All other things being equal, the lower the LFL, the more extensive the flammable cloud from any given release could be and, consequently, the higher the probability and/or shorter the time taken to reach a neighbouring ignition source. Additionally, for identical releases of gases with similar densities and diffusivities, the cloud from the fuel with the lower LFL will persist as an explosion hazard for a longer period.

It is often stated that the minimum ignition energy for hydrogen is much lower than that for almost any other fuel. Whilst this is true, a brusque "So what?" is again warranted. A plot of ignition energy against concentration for hydrogen/air mixtures produces a U shaped graph. Although, the energy needed for ignition at stoichiometry (29.5% H_2 v/v) is, indeed, very low (0.02 mJ) it increases rapidly at lower and higher hydrogen concentrations. At the previously discussed, highly important LFL region the ignition energy of hydrogen is little different to that of the other fuels. Additionally, the energy available from most sparks, even electrostatic discharges from the human body, is usually more than sufficient to ignite any of the fuels under consideration.

In the great majority of instances, hydrogen/air mixtures, in common with the other common fuels, produce a deflagration when ignited. Typically, explosions of this type are characterised by the combustion wave front moving through the unburnt mixture at subsonic speeds. Hydrogen deflagrations are generally assumed to be capable of producing an 8-fold pressure increase, although frequently a much lower value is observed. With hydrogen, however, the likelihood of high levels of congestion or confinement leading to a detonation with supersonic flame speeds and potential maximum overpressures several times greater than those from deflagrations cannot be discounted. The likelihood of the devastating effects of a hydrogen detonation occurring is, however, heavily dependant on the physical environment of the release. Many of the controlling influences are already well known and a lot of work focussed on anticipated hydrogen economy installation and applications is current underway or planned. Consequently, provided that the risk from detonation is recognised, understood and respected, it should not prove to be a major factor in the risk profile for hydrogen.

Several of the arguments above were developed on the explicit condition that the fuels had similar physical properties, e.g. density and diffusivity. However, the very large difference between the values of these properties for hydrogen and those of the other fuels means that the impact of these must be fully considered if an appropriate assessment of the relative risk associated with hydrogen usage is to be developed.

Hydrogen has a very low density, it is much lighter and consequently much more buoyant than the only other lighter-than-air fuel, natural gas. LPG and petrol both form vapours that are heavier than air. The buoyancy of hydrogen and its very high diffusivity, when recognised and effectively harnessed through informed design, can lead to a very significant reduction in the risk from fire and explosion. Once out of the directional, momentum-controlled phase, hydrogen escaping from pressurised systems moves rapidly upwards and, in appropriately designed installations, away from sources of ignition to be quickly dispersed into a safe area. In contrast, petrol and LPG releases tend to remain near the point of release for some considerable time and may spread or roll along the floor some considerable distance until eventually dispersed or ignited.

An additional peculiarity of hydrogen is its behaviour on release or escape through a small aperture. Most compressed gases undergo cooling under these conditions. This reduction in temperature, the Joule–Thompson effect, is an important consideration in industrial liquefaction processes. In many situations when compressed hydrogen is released, however, there is a temperature *rise* across the orifice. This reverse Joule–Thompson effect has been cited by some commentators as an additional and insidious ignition source, further justification for boosting hydrogen up the dangerous substances league table. In reality, the temperature rise is only a few degrees Celsius (NASA, 1997) and, consequently, is unlikely to warrant serious consideration as an ignition source unless the compressed hydrogen is already very close to its ignition temperature (c 585°C).

The "Houdini-like" propensity of hydrogen to escape from containment and its embrittlement of many common fabrication materials means that to control the likelihood of a leak to a tolerable level, much greater effort is required for hydrogen than for other fuels. Furthermore, whilst mercaptans and thiophanes may be used to stench natural gas and LPG thereby greatly increasing the likelihood of early leak detection, chemicals of this type cannot currently be employed with hydrogen. Their sulphur atoms bind irreversibly to the catalyst in the fuel cell membrane and rapidly halt its operation.

To summarise this section, we conclude that hydrogen, in common with the fuels currently in routine use, e.g. natural gas, LPG and petrol, *is* a hazardous material. It is important to note that some of the hazards discussed above are peculiar to hydrogen. These have the potential to markedly increase the risk to those attempting to move in and exploit commercial opportunities in the embryonic hydrogen economy without developing the appropriate underpinning technical competencies. This needs to be effectively communicated to prevent accidents occurring through the assumption that skills acquired with traditional fuels are directly transferable to hydrogen systems.

IS HYDROGEN SAFE? EXPERTS' REPRESENTATIONS OF SAFETY RISKS ASSOCIATED WITH HYDROGEN

Our brief review of hydrogen hazards allows us to place in context the way in which the potential risks associated with the new uses of hydrogen are represented and communicated by scientists, industrial stakeholders and risk assessors to the public (for further discussions see Bellaby *et al.*, 2004 and Ricci, 2005).

In the description of hydrogen properties and hazards, we have offered above, expert accounts provide a relatively consistent picture. However, many different approaches have been taken in extrapolating hydrogen's properties into end-use risk and the assessment of the comparative safety of its use in future scenarios, often leading to conflicting results.

In the previous section, we stated our view regarding the limited use or appropriateness of ranking fuels based on the risks associated with their usage. Consequently, whilst we see little merit in comparative assessments, the following examples of how 'experts' have rated the safety of hydrogen provide an insight into the potential for sweeping, attention-grabbing headlines which may be valid only in the closely defined and sometimes poorly communicated circumstances of the study. These examples are a useful platform for the later discussion of risk perception by the public.

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. 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. While a qualitative assessment of the relative safety of hydrogen as compared to other fuels funded by the National Hydrogen Association (discussed in Cadwaller and Herring, 1999), concluded "*hydrogen is more dangerous than methane and less dangerous than propane*".

Somewhat different conclusions are presented in Barbir (no date available), who argued, for example, that a *hydrogen leak would be less dangerous than a natural gas leak*. Suggesting, somewhat unexpectedly, 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 the fuel.

Attempting to bring some clarity of thought to this issue, Lanz *et al.* (2001) state, "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*". While, in a report prepared for the European

Commission within the European Hydrogen Integrated Project II (EHIP II), Alcock *et al.* (2001) bring significant wisdom to the discussion when they contend 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."

Taken together, these widely diverging opinions reflect the complexity (and redundancy?) of assessing the safety of hydrogen in comparison with conventional fossil fuels. We can only draw very general considerations. Potential risks to the safety of people and the surrounding environment from the use of hydrogen undoubtedly depend upon its physical and chemical properties, which in a few areas appear to be different from those of the fuels currently in use. Appropriate design, training, competence etc. can effect large reductions in the risk profile.

However, focusing solely on properties of the hazardous substance can be misleading on two counts. First, it neglects the variable contexts in which there may be risk of exposure to the hazard. In the case of hydrogen as energy, these contexts vary across the whole life cycle from generation, through distribution, to storage and end use. Part of each context is technological, part is human: how hydrogen is 'handled' at each stage is very material to judging how safe it is. Second, safety ought not to be considered in isolation. Its relevance depends on how the safety of the substance compares with that of other fuels, but also on the calculation of benefits and costs as well as risks in each scenario that unfolds as we move towards a likely energy crisis and try various solutions to avert it and sustain our economy.

A more adequate understanding of risks would therefore encompass not only the physics and chemistry of hydrogen, but also the full range of technologies in which it might act as energy carrier and how those technologies are put to use, installed, maintained and disposed of when obsolete. In short, hydrogen has to be understood as an energy carrier in a complex 'socio-technical system' (as theorised by Bijker *et al.*, 1987), not just as a more or less hazardous substance. This system, made of tangible technologies and intangible components such as knowledge, practices and norms, is as yet only partially evolved and therefore partially understood. The nature, severity and mitigation of risks, therefore, will 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, regulations and operator competence.

This brings us to discuss a further crucial point, one that is not so widely recognised across the literature. Most studies fail to acknowledge the gap that exists between the *present* hydrogen socio-technical system (where hydrogen uses are circumscribed by specific industrial settings) and *future* ones (large-scale retail, domestic and transportation applications), in terms of accumulated contextual knowledge, skills, recommended practices, and regulatory and legal frameworks. Some, however, do offer more guidance in this respect and highlight relevant areas of incomplete scientific and technical knowledge, recommending that under-researched topics be urgently addressed (DOE, 2004).

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). 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 known. Consequently, various recommendations are made for gathering further experimental data on hydrogen leakage and combustion in confined spaces, such as tunnels and garages. 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*". 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*".

Despite an overall effort to address hydrogen safety issues arising from using it as a fuel, no solutions are yet available in terms of widely accepted standards, methodologies, mitigation techniques, and regulations (Dorofeev, 2003). Industrial experience with hydrogen is frequently used to anticipate the nature of potential safety concerns arising from its use as an energy carrier and a vehicle fuel. Industrial production and use of hydrogen as a chemical has gone on for at least 50 years, is well understood, and takes place in well-controlled sites, such as Wilton on Teesside, UK.

According to several industrial Teesside stakeholders, hydrogen is routinely used on-site and transported in containers filled on-site to similarly controlled industrial sites around the UK. Best practices, safety measures, codes, standards and regulations provide a comfort zone in that context, yet they cannot be simply transferred to its use as fuel, partly because they may *inhibit* its development. For instance, familiar industrial safety measures like separation distances, as noted by Moodie and Newsholme (2003), may be impractical and inappropriate for future hydrogen usage scenarios in domestic and mobile applications. Accumulated experience with hydrogen, moreover, is presently limited to a number of industrial applications whose scale and proximity to the general public are small.

New technologies based on hydrogen, such as fuel cell vehicles, create entirely new circumstances of hydrogen usage, which are not covered by industrial experience or through existing codes and recommended practice (HYSAFE, 2005) and are only now beginning to be addressed by research. Examples are the very high pressure gas cylinders (over 700 bar) likely to be utilised by vehicle manufacturers, cryogenic and metal hydride or carbon nanotube storage systems.

Significantly, hydrogen has historically been handled only by highly trained personnel and in extremely controlled environments, where competence and compliance of safety practices is a realised expectation. Nevertheless, despite tight controls in industrial hydrogen installations, accidents have occurred due to accidental releases, mechanical failures and incorrect operations (Moy, 2003; Risø ISI ENEA, 2004). Future uses of hydrogen as a commodity fuel, like natural gas and petrol, will involve an untrained and inexperienced public. Local fuel suppliers and installers, as well as professionals employed in fire or rescue situations, are not familiar with hydrogen and the knowledge they have from handling fossil fuels will prove to be a disturbing mix of the appropriate and the inappropriate.

The present situation is, therefore, one where uncertainties and knowledge gaps abound. A thorough understanding of the practical, realistic contexts in which hydrogen will be used by the public is needed and over time will develop in greater clarity. Despite the present lack of knowledge, hydrogen as the fuel of the future is gaining more and more advocates across countries and disciplines, leading one commentator (Cherry, 2004) to speak about an "unspoken consensus" among the scientific community, which may cause important risk issues to be under-recognised. When communicated to the public this may create undue optimism, which would be deflated if an unexpected explosion or conflagration were to occur involving hydrogen, so damaging confidence in a hydrogen future, as has happened in parallel instances involving 'miracle' drugs. Fortunately, perhaps, sceptics about or opponents of a future hydrogen economy have started to make their voice heard, supporting their views with different arguments. Shinnar (2003) for instance considers hydrogen too hazardous a material to be entrusted with our future, while Romm (2004) highlights outstanding technological and economic limitations.

The issue, however, is not really whether hydrogen is as safe as or less safe than fossil fuels, but:

a) That the hazards, the circumstances in which they are likely to occur, and the handling are qualitatively different; and
b) how the risk is perceived by the public.

The latter point is the core of the following sections.

PUBLIC RISK PERCEPTION: (I) PERSPECTIVES FROM THE SOCIAL SCIENCES

We have argued that using hydrogen as a fuel brings hazards to public safety which may be different from those of the traditional, more familiar fossil fuels, and that these may not be represented adequately in communications to the public about hydrogen as energy carrier. However, risk assessments, safety practices, codes and regulations are being developed in an international effort to make the hydrogen economy a reality.

Neither technical feasibility nor economical viability will wholly determine whether hydrogen substitutes for hydrocarbon fuels. A key role in technological innovation and diffusion is played, in fact, by the way in which technologies evolve and gradually become embedded in social activities. Technologies are then associated with a set of cultural, symbolic and social meanings and become part of routine behaviour. Public attitudes also play a part in deciding which new technologies become mainstream and which do not do so. Numerous studies have showed that public responses to new technologies are influenced, among other factors, by concerns over the risks associated with that particular technology, and by the way in which those concerns are weighed against perceived benefits and costs.

Risk perception has been the focus of academic research for several decades and has interested a wide range of disciplinary areas, including scientific disciplines, economics, psychology, anthropology, sociology and political sciences (for a detailed review of these perspectives, see Weyman and Kelly, 1999; Taylor-Gooby, 2004; and Zinn, 2004).

Psychological research has attempted to analyse how individuals define risks and to understand the key factors influencing such process. Drawing on responses to questionnaire surveys, several factors have been identified as determinants of public risk perception (Johnson and Slovic, 1998; Slovic, 2000; Fishoff *et al.*, 2000; Klinke and Renn, 2002): (a) the "perceived dread", linked to the hazard's catastrophic potential and level of involuntariness in exposure; (b) the extent to which the hazard is known, familiar, detectable, controllable and understood; (c) the number of fatalities or casualties, should the hazardous event occur; (d) whether the effects are immediate or delayed; and (e) the degree of trust in institutional, scientific and regulatory bodies. This framework has been used within the "psychometric paradigm" to understand how lay people perceive the risks from different types of hazards, stemming from industrial installations, technologies, personal habits and diseases. Underpinning these types of studies is, generally, the assumption that a correct (and privileged) way to assess risks exists, and it coincides with science-based risk assessments, whereas lay perceptions are somehow distorted ways of grasping reality. Individuals are modelled as discrete entities, which make choices, decisions, and judgements in isolation on the basis of "objective" information they receive.

From a sociological standpoint, the processes by which risks are identified and perceived are always contextual and deeply rooted in culture and ideology (Flynn *et al.*, 2005). Risks are viewed as socially constructed and the product of different knowledges of the world (Lupton, 1999). Risk perception, therefore, is considered a process embedded in a certain socio-cultural context and not only (or predominantly) the product of individual cognitive processes. Expert assessments and judgements also reflect social values, norms and beliefs.

Although there is not a unique school of thought in risk perception, but rather a variety of conceptualisations within and across different disciplines, there are several aspects which have gained more prominence in recent years.

Trust is increasingly recognised as one important determinant of public responses to new technologies, especially in those cases when expert knowledge is very complex, incomplete, disputed and rapidly evolving. Risk perception can thus be mediated by the level of trust assigned by the public to stakeholders involved in technological development and communication about new technologies. For instance, studies addressing public attitudes to relatively unknown or contested technologies, such as Carbon Capture and Storage, Genetically Modified Food and Organisms, and Nanotechnology (discussed in detail by Flynn *et al.*, 2005), show that public support was conditional upon how people perceived risks associated with specific applications of the technologies, on their views on broader issues, such as the environment and the extent of their trust and confidence in expertise, institutions and industry.

Attention has been brought to the inability of certain risk assessments to fully comprehend and reflect the complexity of real practices, as opposed to the ideal "laboratory" practices. Similarly, evidence suggests that public unease with, or opposition to, new technological development can hinge on a wider, more fundamental set of concerns, which appear neglected in technical accounts. Such concerns relate to questions about the motivations underpinning the development of a specific technology, the legitimacy of those in control of it and the distribution of benefits and risks across society (Irwin, 1995). This has produced new ways of looking at lay understandings (Wynne, 1996) and has encouraged the shift to a more interactive, as opposed to one-way, form of dialogue with the public over the development of technology (Irwin and Michael, 2003).

PUBLIC RISK PERCEPTIONS: (II) HYDROGEN – SOME RECENT FINDINGS

The way people feel about a future development of a hydrogen economy may depend on their current awareness and knowledge about hydrogen, which they might have gained from media reports or other publicly available information. Hydrogen is usually presented in a positive light, and associated with global benefits to the environment and security of energy supply, and local benefits, such the improvement of air quality, and reduction of pollution and noise from vehicles and power-generating technologies. Some websites insist that people would make a link between hydrogen and the bomb or the Hindenburg disaster and fear opposition on safety grounds.

Intensified attention at local, national and international level on the use of hydrogen as a “clean” energy carrier and fuel has not been matched by a comparably high degree of public engagement. Other new technologies, such as biotechnology and nanotechnology, have received far more attention in public debates and the media. As an unfamiliar type of fuel, hydrogen might be expected to trigger public anxiety over its flammable and explosive characteristics, but studies on public perception of hydrogen and its associated technologies are still very few and do not allow us to deduce statistically significant conclusions. Most of those past studies point to a general lack of awareness and knowledge of hydrogen among the lay public.

One of the most recent studies (O’Garra *et al.*, 2005) investigates public attitudes towards the introduction of hydrogen buses in London and attempts to identify key factors underpinning public acceptance. Discussing past evidence on this issue, it is argued that despite a generalised lack of public awareness, hydrogen vehicles do attract relatively high public support. However, it is claimed that past studies have mixed results. Overall, previous findings point at prior knowledge, experience, safety and environmental concerns as having relevant influence on supportive attitudes.

By administering a telephone questionnaire to a sample of 414 London residents, the authors found that over a third of the respondents were supportive of the introduction of hydrogen vehicles in London, whilst the remaining two-thirds needed more information to form their views. Free associations with the word ‘hydrogen’ were mainly neutral, followed by positive and negative associations. According to the authors, “these results suggest that public concerns with hydrogen safety are not likely to be widespread”. Safety concerns, instead, appear to preoccupy the experts more than the surveyed population. The study concludes that prior knowledge about hydrogen appears to increase the likelihood of acceptance, whereas environmental concerns did not seem to influence public support for hydrogen vehicles.

Evidence that attitudes towards the environment may not have a significant role in this respect is in line with previous findings of economic research (some of which are reviewed by Mourato *et al.*, 2004) investigating purchasing intentions and actual choices of transport technologies. Cost, performance and personal benefits emerge as key factors influencing preferences for private transport.

In another study carried out prior to the introduction of prototype hydrogen buses in Amsterdam (Van den Bosch, 2003), a very small sample (22 people) of bus passengers was interviewed. Respondents placed great importance on the environmental impact, smell and noise level of conventional buses and expected that hydrogen buses would make improvements in those areas. Safety was not thought to be a problem by most respondents, suggesting that people were confident that hydrogen buses would be at least as safe as conventional buses.

An empirical study has been conducted in Wales (Cherryman *et al.*, 2005) as part of a programme of activities having the goal of building a regional sustainable economy through the use of hydrogen energy. The fieldwork consisted of a series of focus groups with members of the public living in South East Wales, an area where hydrogen demonstration projects are being planned. The main objective of the research was to understand public perception and acceptability of hydrogen as a fuel. Participants were found to be generally supportive of science and trustful of the regulation of science. They also appeared to be aware of a looming energy crisis, although they were not sure about the timescales involved. Participant were not aware of hydrogen projects in Wales, neither were they informed about hydrogen buses already running in some cities around the world, including London. Different views on safety emerged. Some people felt that transportation technologies would be thoroughly tested before being put on the market, whereas others expressed more concerns about the fact that hydrogen is classified as a “highly flammable” substance. Some people were concerned about accidental releases of hydrogen and other unexpected consequences of water emission from fuel cells. Cost was the principal factor people would consider if they were to choose hydrogen technologies personally. This was true also for participants who were particularly concerned about the environment. People identified government financial support measures as a means to facilitate the uptake of hydrogen, but feared tax increases as hydrogen adoption would be left to market forces alone. People did not welcome a prospective increased fare for hydrogen buses. When faced with the prospect of a massive move to hydrogen in Wales, participants expressed general support, as that would create jobs and make the region more attractive. In summary, the study showed that men (and not women as in other studies) were more sceptical about hydrogen. The two main concerns were safety (both of hydrogen use and in production) and cost, which in particular seemed to override environmental considerations. Biological and renewable energy sources were identified as the most desirable options for hydrogen production.

On-going empirical work with members of the public, conducted within the UK Sustainable Hydrogen Energy Consortium, allows us to make some preliminary comments on public attitudes to hydrogen energy in Teesside. Several important issues emerged from a focus group aimed at understanding the broader context in which hydrogen energy and associated risks are discussed.

Participants were aware of environmental issues associated with the use of fossil fuels and expressed concerns about CO_2 emissions and air pollution. They felt somehow powerless, as the principal CO_2 emitter, the U.S. does not seem to make sufficient efforts to avert the problem. They expressed support of hydrogen as a future energy carrier, however argued that only hydrogen produced from renewable sources would "make sense environmentally". They were particularly supportive of public transport, such as buses, running on hydrogen. As for safety concerns, participants acknowledged that hydrogen is highly flammable and explosive, but assumed that it would be safe if introduced on the market. Refuelling stations, in particular, would need to show good safety records. Stationary applications, such as hydrogen-fuelled CHP for homes, were also supported, however cost appeared a primary determinant for personal adoption. In addition, other forms of energy-saving measures were advocated, such as improving energy efficiency. Participants showed distrust of politicians and there was some debate on the trustworthiness of scientists. They felt that it was important to involve citizens in debates about new technological developments.

It has to be borne in mind that Teesside has been the site of hydrogen generation for 50 years or so. The context and the applications have been industrial, not to do with energy in heating or transport. Hydrogen is an intermediate product in petro-chemical and natural gas processing and is not generated by low carbon methods. Air pollution has also been a controversial issue in the region for many years, the Clean Air Act of 1958 notwithstanding. Thus members of our first focus group in Teesside had considerable knowledge of hydrogen, some from previous employment in the local industry, some as residents, and their views on hydrogen were undoubtedly influenced by the context.

PUBLIC RISK PERCEPTION: (III) DISCUSSION

Findings from risk perception studies have to be carefully handled, as they are valid only in the context in which they were carried out and reflect both the methodology used and the size and type of the population sample. In the case of hydrogen energy, the limited available evidence suggests that safety issues are approached in different ways across the samples and are generally discussed in relation to realistic contexts in which hydrogen energy will be applied and used by ordinary citizens.

An upstream question relates to the extent to which public self-reported attitudes to specific imaginary or prototype hydrogen-based technologies (such as vehicles) still hold significance in different practical contexts where other technologies in the hydrogen system play a more prominent role. If hydrogen energy is viewed from a socio-technical system perspective, a future hydrogen economy can be seen as an ensemble of interrelated technologies. Clean vehicles and smart electronic devices will certainly be at the forefront, but also new production facilities and infrastructures for hydrogen storage and distribution, such as refuelling stations, will necessarily be a visible part of the whole picture. Public reactions to those potential technological developments have not been systematically studied yet.

Nevertheless, not all new technologies give rise to public concerns. The mobile phone is an example of a technology that has been widely and enthusiastically taken up without public fears of unexpected risks to health. Perceived personal benefits are invariably important in the diffusion of new products and research has shown that risks are less likely to be associated with technologies that appear particularly beneficial or useful (Siegrist and Cvetkovich, 2000).

Conversely, hydrogen-based technologies such as FC cars are currently very expensive to manufacture and do not seem to offer to consumers any apparent personal benefits, or added value, compared with conventional vehicles. The prospects for hydrogen will undoubtedly change in the future as the need to replace fossil fuels becomes stronger.

As for transportation applications, it would enable progress towards a hydrogen economy if people trusted to what we know of petrol or natural gas, but a leak and fire/explosion could greatly undermine that trust, since the technology is new its difference from what is familiar to users would get emphasis if there were an accident.

CONCLUSION

We have considered three perspectives in assessing whether hydrogen might be too dangerous to base our future upon: a) the hazards that hydrogen presents, b) how these hazards are represented and communicated in the scientific and popular literature, and finally c) how the public might weigh the benefits, costs and risks of a future hydrogen-based economy.

On the first count, hydrogen *is* hazardous. It is not unique among fuels in this respect, and this fact alone does not tell us anything about the likelihood that hydrogen energy will be encountered in the future as having the same level of risks, costs and benefits as fossil fuels have today. Comparisons between applications of hydrogen today and fossil fuels today are probably misleading, for far more is known about hydrogen's industrial uses than the part it might play as the prime energy carrier for transport and heating, and it is in the industrial context that (largely effective) regulation has been developed. Hydrogen as energy carrier for the future has to be viewed as an element in a complex network of technologies ranging from generation of hydrogen by various means, through different forms of distribution, down to varied end uses. It will also form part of a 'socio-technical system', for there is a key human element to the safety of any technology. Hydrogen devices will have to be installed, used, maintained and disposed of when obsolete, by human beings who will not at first be as familiar with the properties of hydrogen as they are with those of petrol or natural gas. Regulators as well as the public need to focus not so much on whether hydrogen is as safe as petrol and natural gas in some absolute sense, as on the hazards a substance with its properties might present in the many different stages and contexts of it use. It is important that the science of hydrogen safety addresses knowledge gaps and improves both theoretical and practical understandings of hydrogen hazards when it is used as an energy vector. Some risk assessments tend to be 'framed', that is, conducted within parameters that are acceptable to the scientific community at a given time. They focus on the hazards of materials, when tested under controlled laboratory conditions. However, the risks associated with handling under normal conditions of use – that is, when the lay public is directly involved – are less well understood and may be left out of account as 'beyond the frame' of the science.

On the second count, the representation of hydrogen safety in communication among 'experts', and between 'experts' and the public is often contradictory and conflictual. Hydrogen as an energy carrier of the future has its proponents, opponents and a range of sceptics. Among proponents there tends to be an unspoken consensus about the relative safety of hydrogen as compared with fossil fuels, and a tendency to go on the defensive when this is challenged. Among both proponents and opponents there is a tendency to generalise about hazard findings beyond the specifics of the context in which they are generated. The scientific tradition invites us to be sceptical and seek out the conditions under which generalisations apply, being satisfied with nothing less than evidence that is widely replicated.

On the third count, in the context of how publics perceive the risks, costs and benefits associated with hydrogen as a substitute for fossil fuels, safety issues appear to be important but, as yet, not to dominate public debates. More research on public attitudes is needed and this should be carried on as an essential part of the development of a hydrogen economy. How hydrogen compares today with fossil fuels is not necessarily a guide to what it will look like 20-30-40 years ahead when hydrogen is a near economic necessity if we are to continue the transport and central heating ways of life developed countries are used to and more around the world want to emulate. The balance of safety, costs and benefits associated with hydrogen is dynamic and path-dependent. How the public negotiates this trade-off will depend on evolving, rather than static, circumstances: the way in which hydrogen technologies are developed and introduced into the market, and how these relate to inevitable changes in the world energy outlook.

Importantly, we have to consider how (if at all) we can get from here to there without major disruption and/or major global warming and air pollution effects in between. The economics for hydrogen in the short term now do not add up. They are as expected for demonstration projects but far from mass production at realistic prices for consumers, except the very rich. If the very rich alone exploit the opportunity, the relatively poor (countries as well as classes inside richer countries) will suffer loss of amenities as fossil fuels deplete. If only the rich do so, mass production and competitive prices will not come on stream at the right time.

Today hydrogen, indeed renewable energy generally, is a public good not a competitive commodity. To achieve a hydrogen economy we need state or, more productively, inter-state intervention – in order to sell the idea to citizens and create incentives in the market. Part of the price of selling a public good is that the state and stakeholders raise expectations, indeed may be seen as making a promise in exchange for sacrifices now by the public. If part of the expectations is that hydrogen is safe or at least as safe in similar uses as the familiar fossil fuels of the present, the public could be unnerved by a significant accidental fire or explosion associated to with hydrogen in the transition to a hydrogen economy. Engaging with the public and ensuring that the benefits, costs and risks of hydrogen are understood and openly debated (without inappropriate exaggerations on hydrogen inherent safety) is not just a matter of ethics, but one of political expediency.

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APPENDIX 1
HYDROGEN PROPERTIES WITH 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°C	10,050	32,650	86,670	na
Gas at 3,000 psig and 15°C	1,825,000	6,860,300	na	na
Gas at 10,000 psig and 15°C	4,500,000	na	na	na
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

Physical/Chemical characteristics	Hydrogen	Methane	Propane	Petrol
Upper limit (UFL)	75	15	9.5	7.8
Minimum ignition energy (mJ)	0.02	0.29	0.26	0.24
Min autoignition temperature (°C)	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