Development of H_2 Safety Expert Groups and due diligence tools for public awareness and trust in hydrogen technologies and applications

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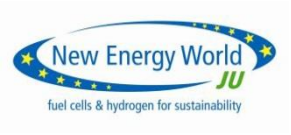

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Public Safety Assessment

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Contents

INTRODUCTION 5
1 SAFETY ANALYSIS OF HYDROGEN PROPERTIES 7
2 REVIEW OF HYDROGEN REGULATIONS AND SAFETY MEASURES 11
3 PUBLIC PERCEPTION OF HYDROGEN SAFETY 18
4 RECOMMENDATIONS ON PUBLIC SAFETY OF LARGE SCALE HANDLING AND TRANSPORTATION OF HYDROGEN 24
BIBLIOGRAPHY 26

Introduction

For decades hydrogen has been safely produced, handled and consumed in industrial environments in vast amounts and in correspondence with set regulations and standards. In the coming years, hydrogen will enter the public domain as a major source of fuel for cars, buses, truck and boats. These vehicles will be driven by electric engines, which get their energy from the conversion of hydrogen gas into electricity emitting water as a by-product. Although proven operated safely in industrial settings, the use of hydrogen in the public domain is still a recent development. A viable hydrogen infrastructure requires adequate storage facilities, refuelling stations and a large-scale transportation network for hydrogen. The large scale transportation of hydrogen is a critical piece of the infrastructure required to support the deployment of hydrogen fuel cell vehicles on a commercial scale. Its efficiency, reliability and safety are critical for the successful implementation and market and public acceptance. Public awareness and perception of the use of fuel cells and hydrogen (FCH) for transportation and mobility are part related to the safety as perceived by the public. In this report a safety assessment of the large scale transportation of hydrogen is conducted.

This Report is intended to determine the extent to which the public knows and understands what is happening as regards FCH applications, how they will change with time, how they will influence them as regards safety and who are the other stakeholders in the environment. The first step would be to investigate the current situation, to provide guidelines in view of large scale deployment of FCH applications. The second step would be to help write the benchmarks and instructions for inspection and enforcement by authorities. The purpose of the task is to provide a risk assessment on behalf of the public interest and advice on risk mitigation measurements, guidelines, benchmarks, training of officials and regulations that improve the safe production, transportation and use of FCH. This will be a key input to the dissemination phase (Work Package 5 of H_2TRUST) to ensure that the public understands the risks and the required caution with handling of hydrogen.

The approach and methodology applied for this Deliverable is based on a quantitative study of literature, research data and state of the art reviews on this field of expertise. This study provides a safety analysis of hydrogen properties, an overview of the hydrogen related regulations, codes and standards that are currently in place and provides an overview of risk mitigation measures, training guidelines, benchmarks, etc relevant to the transport, production and storage of hydrogen. The quantitative study continues with an investigation of the public's understanding about hydrogen fuel cells technology and applications as well as the safety of hydrogen fuel cell technology.

The document comprises 4 chapters (one for each of the areas outlined above) and a summarizing paragraph:

- ***Chapter 1: Safety analysis of hydrogen properties***
- ***Chapter 2: Review of hydrogen regulations and safety measures***
- ***Chapter 3: Public perception of hydrogen safety***
- ***Chapter 4: Public safety of large scale handling and transportation of hydrogen***

These chapters provide a risk assessment on behalf of the public interest and advice on risk production, transportation, and use of hydrogen technology. This will lead to recommendations for benchmarks and instructions for safety inspection and enforcement by authorities as well.

1 Safety analysis of hydrogen properties

When considering the public safety of the large-scale handling and transportation of hydrogen in the public domain, an appreciation of its possibly hazardous properties should be made. All fuels have some degree of danger associated with them, hydrogen is no different. A number of hydrogen's properties make it safer to handle and use than the common fuels used today. However, some properties of hydrogen are different from other fuels and have to be considered when handling hydrogen instead of, for example, petrol, gasoline or natural gas.

These aspects have been also addressed in "D 3.1 - State of play H_2 issues", where a deeper analysis of the main characteristics of the gas H_2 with reference to safety-hazard-risk has been made for the five categories of the H_2TRUST project (1. Production; 2. Storage and Distribution; 3. Mobility and Vehicles; 4. Non-vehicles and residential power generation; 5. Regulators, 1st Responders, Consumers).

Properties of hydrogen

For an analysis of the public safety of hydrogen it is important to know its most significant physical, chemical and biological properties that can be addressed. This paragraph describes the properties of hydrogen relevant to its safety. Table 1 provides the principal characteristics of hydrogen and several conventional fuels.

Table 1. *Characteristics of hydrogen and conventional fuels*

	Unit	Hydrogen	Gasoline	Diesel	Natural gas	Methanol
Chemical composition		100% H	85% C 15% H	87% C 13% H	75% C 25% H	37.5% C 12.5% H 50% O
Density (gas/liquid)	kg/m^3	0.0899 70.8	4.88 700-755	- 820-930	0.717 415	- 791
Diffusion coefficient in air	m/s	$0.66*10^{-6}$	-	-	-	$0.186*10^{-4}$
Feature temperatures: - boiling start - boiling finish - ignition - freezing - maximum combustion in air	K	 20.2 20.2 823-897 11 2503	 313 453 773-793 213 -	 - - 593-653 213 -	 111.4 - 923-973 90.4 2316	 337.7 - 741 175.2 2175
Stoichiometric air quantity	kg/kg	34.2	14.9	14.3-14.7	17.25	6.47
Inflammability limits" - inferior - superior	% vol	 4 75	 0.59 6	 - -	 5.5 15	 - -
Vaporization energy (20ºC)		451-476	292-314	18	5111	1105
Ignition energy	kJ/kg	20	250	-	-	-
Inferior heat power	MJ/kg	121	43.744	42.5	49.79	19.3
Combustion speed	m/s	2.7	0.4	0.4	0.36	-

Physical, chemical and biological properties

Hydrogen is a colourless and odourless gas and the simplest and the lightest of all elements. At normal atmospheric conditions hydrogen has a very low density of 0,09 kg/m^3, which is about one fourteenth that of air. Apart from a low density, hydrogen gas has a very low viscosity, is highly diffusive and is easily ignited. Hydrogen is not exceptionally reactive and coexists harmlessly with free oxygen until an input of energy drives the exothermic reaction that forms water.

The characteristics of hydrogen result in several disadvantages of hydrogen in comparison to other common fuels. Hydrogen, for instance, is not corrosive but depending on temperature, pressure and other conditions it may cause embrittlement of certain steels, resulting in cracking and failure of these metals at stresses below yield stress. Metal alloys with a carbon content, such as high strength steels, titanium and aluminium alloys, are most susceptible to embrittlement due to hydrogen. In industry, standards are in place for steel components used for hydrogen. Furthermore, due to its very low viscosity hydrogen has the propensity to easily diffuse through small openings and porous materials such as welds, flanges, seals, gaskets, which would be sufficient to conceal other gasses. As a result, it is very difficult to prevent hydrogen systems from leaking. The likelihood of leaking can be significantly reduced through the usage of hydrogen suitable interfaces and components. The energy leakage rates associated with hydrogen leaks are however lower than those of, for instance, natural gas and propane due to the low density of hydrogen. As mentioned before, hydrogen is much lighter than air and is highly diffusive, meaning that when a leak occurs hydrogen diffuses rapidly in well-ventilated areas. Moreover, hydrogen has a wide range of flammability both in air and oxygen, ignites easily because of a low ignition energy and mixes well with air creating risk for explosions in enclosed areas where it will rise and concentrate in elevated areas due to its buoyancy over air.

Other hazards related with hydrogen are:

- **Confined mixtures of hydrogen and air or oxygen explode very strongly and may detonate**. In practice, hydrogen venting or leaking to atmosphere (particularly from a pressure source) can ignite due to electrostatic or self-igniting impurities in the hydrogen. However, An unconfined gas cloud explosion of hydrogen is very unlikely to occur and no such detonations have been reported.

- **Hydrogen burns with a hot flame and produces no soot resulting in a pale, colourless flame almost invisible in daylight.** As the heat radiated by a hydrogen flame is also relatively low a hydrogen flame gives little warning of its presence either by sight or heat.

- **Hydrogen flames, especially those emanating from a high-pressure source, are difficult to extinguish**. The best way of extinguishing is to shut off the flow. As mentioned earlier, hydrogen gas is odourless, colourless and tasteless and therefore not detectable by human senses.

- Although hydrogen gas is not toxic it displaces oxygen and can therefore act as an asphyxiate. Breathing hydrogen causes loss of consciousness and imminent death.

Properties and effects of liquid hydrogen

Hydrogen is generally stored and transported in a liquid or gaseous state. When transported in liquid state, insulated thermic reservoirs at about 20K (-253ºC) are used. Storage and transportation of liquid hydrogen poses no additional difficulties than for other flammable gaseous liquids. As hydrogen is stored and transported in liquid state as well, some additional safety aspects regarding liquid hydrogen also have to be taken into account. Like gaseous hydrogen, liquid hydrogen evaporates rapidly when spilled to the atmosphere. One litre of liquid hydrogen is the equivalent of about 850 litres of gaseous hydrogen in normal atmosphere. Liquid hydrogen can cause cryogenic burns when in contact with skin. Delicate tissue, such as those of the eyes can be injured by exposure to the cold gas or splashed liquid in a brief period of time, which would normally be too short to affect the skin of the hands or face. Uninsulated piping or reservoirs containing liquid hydrogen can cause the flesh to stick and tear. Cold boil-off hydrogen is a little denser than air and may accumulate in pits and trenches, for short periods depending on temperature and quantity. After that hydrogen rises and diffuses rapidly. Cold boil-off hydrogen condenses the moisture in the air, thus creating a highly visible fog. At the temperature of liquid hydrogen all gases, except helium, condense and then solidify. The resulting solid particles can block valves and orifices, which could lead to a failure of flow and/or pressure increase. Furthermore, condensed or solidified air in liquid hydrogen is a potential explosion hazard. Liquid hydrogen has a very low heat of vaporisation, meaning that a small heat input will create a violent evolution of gas and splashing of liquid. Moreover, liquid hydrogen in poorly insulated containers and piping will liquefy the surrounding air. Due to the different boiling points of nitrogen and oxygen condensed air is oxygen-enriched and can cause a fire risk.

Safety aspects and recommendations regarding hydrogen fuel

Hydrogen has comparable characteristics to other (gaseous) fuels and, as a result, common safety measures and guidelines for gaseous and liquid fuels are in most cases also applicable to hydrogen fuel. However, hydrogen has several characteristics which significantly differ from today's conventional fuels, and which have to be taken into account, specially, during transportation and storage. As described, the large scale transportation and storage of hydrogen present the following safety aspects that have to be considered:

- Hydrogen can cause embrittlement of certain steels, resulting in failure and leakages. When designing hydrogen systems industrial standards have to be applied regarding the carbon content in metallic alloys.
- Gaseous hydrogen has a propensity to leak due to very low viscosity, requiring specific hydrogen suitable materials and components. Therefore, hydrogen leakage should be considered in the design and use of hydrogen systems.

- Hydrogen has a buoyancy over air and rapidly diffuses causing potential risk of explosion in enclosed areas. Hence, when hydrogen is used in enclosed areas, a hydrogen system should only be place in well-ventilated (or open) environments.
- Due to a very low ignition energy hydrogen is easily ignited and exhibits wide limits of flammability, which causes thermal and fire hazards especially in enclosed areas. In open, well-ventilated areas hydrogen is significantly less dangerous due to its rapid diffusion.
- Hydrogen is non-toxic, colour-, odour- and tasteless and is non-detectable by humans senses. Although non-toxic hydrogen gas replaces oxygen and it can cause suffocation. Some form of detecting sensors (i.e. acoustic alarm) or other means (i.e. gas colouring) could be put in place to detect and give alert on the presence of hydrogen.
- Liquid hydrogen can cause cryogenic burns when in direct or indirect contact.

These safety aspects are to be embedded in relevant regulations, codes and standards on hydrogen and potential risks are to be mitigated with suitable safety measures, training and instructions, guidelines and benchmarks.

2 Review of hydrogen regulations and safety measures

In the coming years it is foreseen that the use of hydrogen will change from a solely enclosed industrial usage to the use as an energy sources in the public domain as well. The industrial use has been taking place for many years and, as a result, relevant safety codes and standards, as well as practical guidelines and safety measures, have been developed for industrial applications of hydrogen. To ensure safety and minimize the risk of accidents and hazards for the general public, Regulations, Codes and Standards (RCS) and appropriate guidelines and safety measures should also be in place for the production, transportation and storage and use of hydrogen for non-industrial applications in the public domain.

Regulations, codes and standards

Directives and regulations on hydrogen are developed and enforced by (inter)national government organisations to ensure the safety of workers, public, property and the environment. EU member states are required to implement the minimum regulations as set by the European Commission and UN/ECE, into their national legislation. As long as they are not conflicting with these minimum regulations, Members States can implement more extensive regulations, if deemed necessary. Standards and codes (codes of practice) can be considered as best practices in which industry and other organisations with suitable knowledge and competence produce guidelines for technology, production methods, analysis techniques, monitoring procedures, inspection, maintenance, control etc. Standards are not legal requirements and are intended to support the free exchange of goods and services through achievement of common goals. Standards may however be included or referred to in regulations and through the regulation be made legally binding. While standards are developed by standardisation organisations through a thorough development processes involving workgroups consisting of a wide range of interested parties, codes may be developed by a few or only a single company or association. Because of the more rigorous development process standards generally have a wider acceptance than codes.

In general, European standards are developed through the platforms provided by one of the three European Standards Organisations, the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI). In the case of CEN and CENELEC, European standards are developed according to the principles of national delegation, whereby their members - the National Standards Bodies (NSBs) of the EU Member States and the EFTA states - are responsible for developing European consensus. Industry is a key player - whether as a direct member of the process in ETSI or through the national delegations in CEN and CENELEC. SME representation is reinforced by Small Business Standards (SBS).

Overview of regulations, codes and standards on hydrogen

The aim of this paragraph is to provide an overview of the of current regulations and standards on the large scale handling and transportation of hydrogen. The regulations, standards and codes presented here are generally not developed exclusively for hydrogen facilities and, thus, some parts or articles may not be applicable. Apart from these general RCS, there are a limited number of regulations or standards solely aimed at hydrogen handling and transportation. Several hydrogen specific international codes and standards are presently still under development. Below is a non-exhaustive list of hydrogen related regulations, more focused towards the EU Regulations. More information on RCS framework, status and relevant documents can be found in Chap 5 of D3.1, prepared by FAST/HEA.

1	Title	**International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)**
	Summary	International standard for the safe transport by sea in bulk of liquefied gases and certain other substances, by prescribing the design and construction standards of ships involved in such transport and the equipment they should carry so as to minimize the risk to the ship, its crew and to the environment, having regard to the nature of the products involved.
	Author	IMO International Code
	Source	http://www.imo.org/environment/mainframe.asp?topic_id=995

2	Title	**Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)**
	Summary	General provisions and provisions concerning dangerous articles and substances in road transport
	Author	UN ECE
	Date and source	2013 / http://www.unece.org/trans/danger/publi/adr/adr_e.html

3	Title	**European Agreement on the International Carriage of Dangerous Goods by Rail (RID)**
	Summary	International carriage of goods by rail
	Author	Intergovernmental Organisation for International Carriage by Rail
	Date / source	2010 / http://www.otif.org/en/law.html

4	Title	**Inland transport of dangerous goods Directive**
	Summary	This directive establishes a common regime for all aspects of the inland transport of dangerous goods, by road, rail and inland waterways within the European Union
	Author	EC
	Date and source	2008 / http://europa.eu/legislation_summaries/transport/rail_transport/tr0006_en.htm

5	Title	**European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (AND)**
	Summary	The Regulations annexed to the ADN (click here for the original version of 2000) contain provisions concerning dangerous substances and articles, provisions concerning their carriage in packages and in bulk on board inland navigation vessels or tank vessels, as well as provisions concerning the construction and operation of such vessels. They also address requirements and procedures for inspections, the issue of certificates of approval, recognition of classification societies, monitoring, and training and examination of experts
	Author	EN ECE
	Date and source	2008 / http://www.unece.org/trans/danger/publi/adn/adn_e.html

6	Title	**UN Recommendations on the Transport of Dangerous Goods,**
	Summary	Recommendations relevant to hydrogen are UN 1049 (Hydrogen, Compressed), UN 1066 (Hydrogen, refrigerated liquid) and UN 3468 (hydrogen in a metal hydride storage system)
	Author	UN ECE
	Date and source	http://www.unece.org/trans/danger/publi/unrec/12_e.html

7	Title	**Dangerous Substances Directive: 67/548/EEC**
	Summary	Commission Directive 2009/2/EC of 15 January 2009 amending, for the purpose of its adaptation to technical progress, for the 31st time, Council Directive 67/548/EEC on the approximation of the laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances
	Author	European Union
	Date and source	2009 / http://eur-lex.europa.eu/JOHtml.do?uri=OJ:L:2009:011:SOM:EN:HTML

8	Title	**Low Voltage Directive (LVD) 2006/95/EC**
	Summary	Directive on electrical equipment design for use within certain voltage limits
	Author	European Union
	Date and source	2007 / http://ec.europa.eu/enterprise/sectors/electrical/files/lvdgen_en.pdf

9	Title	**Electromagnetic Compatibility Directive (EMC) 2004/108/EC**
	Summary	The main objective of the EMC Directive is thus to regulate the compatibility of equipment regarding EMC.
	Author	European Union
	Date and source	2010 / http://ec.europa.eu/enterprise/sectors/electrical/files/emc_guide__updated_20100208_v3_en.pdf

10	Title	**Pressure Equipment Directive (PED) 97/23/EC**
	Summary	Its purpose is to harmonise national laws of Member States regarding the design, manufacture, testing and conformity assessment of pressure equipment and assemblies of pressure equipment
	Author	European Union
	Date and source	2002 / http://ec.europa.eu/enterprise/sectors/pressure-and-gas/documents/ped/index_en.htm

11	Title	**Simple Pressure Vessels Directive (SPVD) 2009/105/EC**
	Summary	This directive provides guidelines for any welded vessel subjected to an internal gauge pressure greater than 0,5 bar which is intended to contain air or nitrogen and which is not intended to be fired
	Author	European Union
	Date and source	2009 / http://ec.europa.eu/enterprise/sectors/pressure-and-gas/documents/spvd/index_en.htm

12	Title	**Transportable Pressure Equipment Directive (TPED)**
	Summary	Directive on enhancing transport safety for transportable pressure equipment, whilst ensuring the free movement of transportable pressure equipment in a single transport market.
	Author	European Union
	Date and source	2010 / http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:165:0001:0018:EN:PDF

13	Title	**Gas Appliances Directive (GAD)**
	Summary	The scope of the GAD is restricted to appliances burning gaseous fuels used for cooking, heating, hot water production, refrigeration, lighting and washing, i.e. the GAD covers mainly common consumer and commercial products
	Author	European Union
	Date and source	2009 / http://ec.europa.eu/enterprise/sectors/pressure-and-gas/documents/gad/index_en.htm

14	Title	**Equipment and protective systems for potentially explosive atmosphere Directive (ATEX)**
	Summary	The Equipment and Protective systems intended for use in Potentially Explosive Atmospheres (ATEX) provides the technical requirements to be applied and the relevant conformity assessment procedures before placing this equipment on the European market
	Author	European Union
	Date and source	2014 / http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:JOL_2014_096_R_0309_01&from=EN

15	Title	**Directive on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres (ATEX)**
	Summary	This directive provides requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres
	Author	European Union
	Date and source	http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31999L0092:en:NOT

16	Title	**Machinery Directive (MD)**
	Summary	the Machinery Directive 2006/42/EC provides the regulatory basis for the harmonisation of the essential health and safety requirements for machinery at European Union level
	Author	European Union
	Date and source	2010 / http://ec.europa.eu/enterprise/sectors/mechanical/machinery/

17	Title	**Seveso III Directive**
	Summary	Rules for the prevention of major accidents which might result from certain industrial activities and the limitation of their consequences for human health and the environment.
	Author	European Union
	Date and source	2012 / http://ec.europa.eu/environment/seveso/index.htm

18	Title	**Measures to encourage improvements in the safety and health of workers**
	Summary	This Directive establishes obligations for employers and workers, in particular to limit accidents at work and occupational diseases. This Directive should also improve the training, information and consultation of workers.
	Author	European Union
	Date and source	http://europa.eu/legislation_summaries/employment_and_social_policy/health_hygiene_safety_at_work/c11113_en.htm

19	Title	**Personal protective equipment Directive (PPE)**
	Summary	It is a must for PPE, the products having the unique feature to provide for protection against specific hazards, to meet this challenge: to ensure the user's safety and health in specific circumstances. The manufacturer informs about the type of hazards against which his product

		protects.
	Author	European Union
	Date and source	http://ec.europa.eu/enterprise/sectors/mechanical/documents/legislation/personalprotectiveequipment/

20	Title	**SAFETY STANDARD FOR HYDROGEN AND HYDROGEN SYSTEMS**
	Summary	Guidelines for Hydrogen System Design, Materials, Selection, Operations, Storage, and Transportation
	Author	National Aeronautics and Space Administration (NASA)
	Date and source	2006

21	Title	**Basic Considerations for the Safety of Hydrogen Systems**
	Summary	Standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen. Revision of ISO/TR 15916:2004 will provide guidelines for the use of hydrogen in its gaseous and liquid forms. It will identify the basic safety concerns and risks, and describe the properties of hydrogen that are relevant to safety. Detailed safety requirements associated with specific hydrogen applications will be treated in separate international Standards
	Author	International Organization for Standardization (ISO)
	Date and source	2014 / http://www.iso.org/iso/iso_technical_committee%3Fcommid%3D54560

The purpose of RCS on hydrogen is to ensure safe and reliable construction and operation of a hydrogen -related products and facilities for production, distribution, storage, etc. In general terms, RCS mostly follow the development of new technologies and are developed when these innovative technologies are not sufficiently covered by available RCS. This is no different for the deployment of hydrogen in the public environment. With regard to RCS there is a clear need for hydrogen economy applications to have suitable safety standards to ensure safe design, installation, operation etc. As rate of installations increases, standards are essential for safety and to remove potential bottlenecks that could slow development. Large-scale handling and storage of hydrogen is mostly still covered by general industrial RCS. Gap analyses have pointed out that significant gaps exist with regard to refuelling, handling and storage of hydrogen in the public domain. As an example, the 2010 gap analysis conducted by the US National Renewable Energy Laboratory amongst others pointed out that a lack of familiarity of codes and standards on hydrogen exits among project developers. It also identified incomplete requirements for RCS on high-pressure storage, handling and use as well as sensing technologies. The Directive[1] of the European Parliament and of the Council on the deployment of alternative fuels infrastructure (among them hydrogen), approved on 29/09/2014, aims to overcome this gap by addressing the missing links of the single transport market:

• The build-up of an EU-wide network of recharging and refuelling points;
• The development of harmonized EU-wide standards and common technical specifications;
• The provision of relevant, consistent and clear consumer information.

[1] http://ec.europa.eu/transport/themes/urban/cpt/index_en.htm

In addition to this, interviews with stakeholders on RCS and hydrogen, included in the deliverable 3.1 of the H_2TRUST project, brought forward that although current regulation is perceived as sufficient, on a national as well as international level there is limited harmonization and a greater alignment would be welcome. Some interviewees of the CHIC-project[23] research estimated that *'the lack of experience in safety related and authorizing issues could not be remedied by a simple information exchange but required national or international safety regulations, standardized processes and centralized information flows. Without these supporting structures, implementing FCH technologies remained complicated and time consuming for applicants, authorities and the fire brigade. Ambiguous regulation, safety concerns and a lack of experience can be summed up as negatively influencing the acceptance process, as they not only resulted in an uncertainty among the regional stakeholders but also in supposedly "over-engineered" safety measures'*. Suitable codes and standards are essential for hydrogen to become a significant energy carrier and fuel and create a market-receptive environment that offers commercialization opportunities for hydrogen-based products and systems.

Mitigation measures and guidelines on hydrogen safety

For many years hydrogen has been handled in large quantities in industrial and aerospace applications. During that time industry has developed a safe infrastructure to produce, distribute, store and use hydrogen in industrial settings. This has resulted in a thorough practical experience and has provided guidelines for the safe industrial handling and use of hydrogen. In addition to this, many practical pilot and demonstration projects have provided valuable information and experience of specific hydrogen application areas. It is not our aim here of gathering all available documents and information issued on safety measures and guidelines, but to give an idea on the main mitigation measures and trends put in place concerning safety and hazard of hydrogen. For this reason, below several examples of hydrogen safety practices and guidelines are listed that provide insights on the type of documents available:

- *HYSAFE - Safety of Hydrogen As an Energy Carrier* [2009]. This report focuses on the use of hydrogen in confined spaces and the necessary safety measures to be taken. http://www.hysafe.org/download/1710/HYSAFE_D113_version_1.1.pdf].
- *HyFacts – Identification, Preparation and Dissemination of Hydrogen Safety Facts to Regulators and Public Safety Officials* [2013]. The HyFacts project has developed and will disseminate fully up-to-date contemporary material for customized training packages for regulators and public safety experts providing accurate information on the safe and environmentally friendly use of hydrogen as an energy carrier for stationary and transport applications under real conditions. *http://hyfacts.eu/*

[2] Hoelzinger N., Luedi-Geoffroy N (2013), CHIC project, Influencing factors to the acceptance process of FCH technologies in public transport- Deliverable No. 3.5.

[3] Whitehouse S, Whitehouse N (2013), CHIC Project, Clean Hydrogen in European Cities, Issues of concern to external stakeholders and critics and pathways to their resolution. Deliverable No. 3.8

- *Safety Planning Guidance for Hydrogen and Fuel Cell Projects* [2010]. This guidance document provides information on safety requirements for hydrogen and fuel cell projects. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/safety_guidance.pdf].
- *Installation permitting guidance for hydrogen and fuel cell stationary applications* [2009]. This document provides guidance to foster the use and facilitate installations for hydrogen and fuel cell stationary applications. http://www.hse.gov.uk/research/rrpdf/rr715.pdf
- *The Hydrogen Fuel Cell Engines and Related Technologies Course Manual* [2001]. This document features technical information on the use of hydrogen as a transportation fuel. It covers hydrogen properties, use, and safety as well as fuel cell technologies, systems, engine design, safety, and maintenance. http://energy.gov/eere/fuelcells/hydrogen-fuel-cell-engines-and-related-technologies-course-manual
- *Hydrogen Safety Best Practices online manual* [website, continuously updated]. The purpose of this online manual is to share the benefits of extensive experience by providing suggestions and recommendations pertaining to the safe handling and use of hydrogen. http://h2bestpractices.org/
- *Hyindoor* [website, continuously updated] addresses knowledge gaps regarding indoor hydrogen accumulations, vented deflagrations, and under-ventilated jet fires. The generated knowledge will be translated into safety guidelines, including specific engineering tools supporting their implementation. http://www.hyindoor.eu/

In general, hydrogen causes no more safety concerns than other flammable, gaseous fuels, and must be used equally responsibly. Hydrogen can be handled safely as long as users are familiar with the characteristics of hydrogen and act according to available guidelines. However, current guidelines are mainly focussed on the industrial application of hydrogen. The question is if these industrial guidelines are in all cases suitable or replicable for the use of hydrogen in public. **Limited information was found on specific guidelines for the handling, storage and use of hydrogen in the public domain**. Projects already conducted in the public area (such as pilot and demonstration projects) could provide input for suitable guidelines and mitigation measures in the public domain. Indeed, projects which are currently being conducted in the public area already focus on spreading 'lessons learned' by using several platforms (e.g. HIAD database, public deliverables, dedicated dissemination sessions).

3 Public perception of hydrogen safety

The interest in hydrogen as a fuel has significantly increased on European and International Level as a response to increasing concerns on environmental, sustainable energy and safety issues of fossil fuels. Worldwide there have been large investments in research, innovation and demonstration projects to investigate the potential and safety of hydrogen and to develop hydrogen fuel cells. Moreover, there has been great interest in hydrogen fuel (safety) in relation to questions about public perception and acceptance. To date, public's opinion towards new fuel technologies has been studied under different initiatives, also investigating the public opinion about the safety of hydrogen fuel cells. This task in the H_2TRUST project provides a review of the findings of the recent literature on acceptance, attitudes and preferences for (safety of) hydrogen and fuel cell technologies.

Public perception on hydrogen

Public acceptance and their opinion about the safety of hydrogen influence the success of the implementation of hydrogen technologies in Europe, since as a result of a perceived safety hazard, people may decide whether or not to use hydrogen technology or might protest against refuelling stations that are planned near their living area. Therefore, even if technological bottlenecks have been solved, the public needs to be informed of the advantages and safety of this valuable energy carrier to increase the deployment of it. Hence, it is indispensable to look at how the public perceive hydrogen as a fuel and look at their attitudes, fears and expectations. According to several behavioural studies (e.g. Huijts et al, 2010), public opinion is formed mostly by a layman costs-benefit analyses and the public choose options with the highest gains against the lowest costs. These studies suggest that attitudes, subjective norm and perceived behavioural control influence intentions to act, which in turn influences behaviour. Applied to technology acceptance, attitudes are evaluative judgements of the technology and behaviours in response to the technology that influence intention to perform technology related behaviours. Hence, **the public opinion about a topic or new technology is the result of a summed evaluation of perceived attributes related to the new technology and the associated benefits, costs and risks**. Other studies indicate that the public opinion is mostly based on benefits versus costs of a new technology. For example, one hydrogen acceptance study (Molin et al., 2007) showed that preferences for hydrogen vehicles are highly influenced by costs (fuel price and vehicle purchase cost) and convenience factors (detour and range). Moreover, the study indicates that the education level of an individual is very important for an increasing acceptance of hydrogen as a new technology. However, other studies (Huijts et al, 2012) suggest that public's opinion is merely based on what 'feels' best. Then, negative feelings such as fear for the safety of the use of hydrogen as a fuel or fear for the safe transportation and localisation of hydrogen can obstruct public's acceptance of hydrogen technology (Hickson 2006, Montijn-Dorgelo and Midden, 2008).

Henceforth, several studies on public opinion on new technologies and hydrogen fuel cells provide different assumptions about what influences the public opinion. Overall, it can be concluded that the **public opinion is based on a wide range of variables, such as benefits, costs, risks, social**

effect/status of a new technology such as hydrogen fuel cell technology. Moreover, it has to be taken into account that public opinion is a subjective matter and depends on personal factors (e.g. educational background, cultural endeavours, area/region of living, interests, age, awareness of alternative fuel technologies, etc..) as well.

Public opinion on hydrogen fuel

Hydrogen fuel cells have emerged as a promising alternative fuel technology in relation to current fossil fuels. Although the idea of hydrogen as a fuel source is a relatively new concept in response to seeking an alternative to oil, the first hydrogen fuel products were developed in the early 19th century. So far, the hydrogen energy market has been centred on the petroleum refinery and chemical manufacturing sectors. However, since approximately 5-10 years, interest for the usage of hydrogen in the fuel cell sector and replacement of petroleum refining and chemical manufacturing has significantly increased. In relation to the increase of the interest of the industry and governments, also public assessable information about hydrogen and alternative fuel technologies has increased. Up to now, most of knowledge on hydrogen fuel technology has been spread by specialized journals or websites. Although the media coverage on hydrogen has increased, the mass media still does not cover the hydrogen as an alternative fuel technology.

In addition, there is relatively limited information available on public perception about hydrogen technology and the public opinion about hydrogen technology as a future alternative fuel. Studies performed on the public opinion about hydrogen fuel are mostly conducted in the United Stated and Canada. Some material is available on studies performed in European countries such as Germany, Iceland, The United Kingdom and The Netherlands (e.g. Fuhrmann et al 2007, Hickson et al 2006, Maack et al 2006, O'Garra, 2005). Most of these European studies specifically focus on hydrogen use in transportation technologies. The **main results of the European studies** are reflected in five different contexts below, **generally indicating that the public is unconcerned and positive about hydrogen fuel technology as a potential alternative for current fossil fuel systems.**

GENERAL PERCEPTION

- Interviewed participants to these studies articulated that **more demonstration projects** might inspire and encourage future developments. Moreover, the lack of demonstration projects and the non-continuation of a project after ending its demonstration phase (together with the information about these demonstrations and outcomes to the general public) is generally seen as detrimental to their development and public acceptance.
- Participants indicated that **costs might inhibit development** and restrict the commercial viability of potential product applications. This supports the findings of the European High Level Group (EC, 2003) where it is poined out that hydrogen and fuel cells do not currently offer sufficient short-term end-user benefits to justify their high costs compared to conventional technologies.
- However, other studies indicate that participants recognise that the production of hydrogen from natural gas is currently the most economically viable method and that **fuel cells may need to go**

through a transition phase of using natural gas before biomass and renewables as a hydrogen production source.

- **Fuel cells and hydrogen** technology are **still regarded as being a relatively 'young'** technology and therefore still having much to prove as an alternative means of energy generation.

ENVIRONMENT

- The overall impression from the participants was that **stationary fuel cells offer a significant way forward towards sustainable energy**.
- The **lack of evidence that fuel cells are significantly less damaging environmentally than conventional power sources when fuelled by hydrogen produced from fossil fuels** remains a key concern for several participants. However, a number of interviewees recognised the benefits from reduced local pollution and quiet operation - an important concern in an urban environment.
- The potential economic and environmental benefits of hydrogen technology is foreseen as a potential important piece of a sustainable transportation systems in Europe.

RISKS AND SAFETY

- Only one report mentioned safety specifically on national and regional level. This report was in line with other studies on hydrogen safety and reflects that although hydrogen projects have so far been perceived as safe, the **safety of hydrogen is still a topic of concern**.
- History has shown that the **public perception** on the risks and safety of hydrogen **can be long-term negatively influenced by hydrogen related incidents** (such as the Hindenburg disaster). This is not unique to hydrogen technology, but is **applicable to most emerging technologies**.
- Studies show that the risk **perception of the public is influenced by several factors**, amongst which the level of knowledge and information about the new technology.

KNOWLEDGE LEVELS & EDUCATION

- The interviewed participants recognised the need to **extend the knowledge base** for hydrogen technology, to improve their efficiencies, reliability, lifetime and material performances.
- Some studies suggest that **gender or age did not play a role in the attitude** towards using hydrogen as a fuel.
- Many studies report a relatively **low level of knowledge on hydrogen**, implying that the public does not yet have an informed view.
- **Outreach activities** have generally only informed the public near of demonstration projects, leaving the larger public uninformed.

POLICY

- It was widely felt that the **Government has not shown sufficient support** for hydrogen applications to date and that further backing will be necessary to enable hydrogen technology to reach the market.

- For the participants in one research the **key barriers** to the development of fuel cells relate primarily to **governmental and legislative issues**.
- For most of the participants 'government support' includes **financial support**, through some form of **subsidy or taxation**.
- Further development of the domestic energy resources is on policy agenda of multiple EU countries and the EC. The EC recognises that it is important to invest in domestic energy resources to support the EU economy.
- Participants in surveys indicate that **hydrogen fuel deliverance might not easily be connected to energy services throughout Europe** and this should be taken into consideration by governmental bodies.

The results of the **studies show a significant increase of the knowledge** regarding hydrogen in general and an increase of awareness of hydrogen as a potential alternative fuel technology. For example, studies performed between 1998 and 2005 show a large variety in positive and negative associations to hydrogen. Moreover, the studies confirms that knowledge on hydrogen is relatively low but indicate that **the public is open and interested** towards the technological and environmental potential of hydrogen usage. Especially people working in the transportation sector believe that hydrogen has the potential to replace conventional fuels in the future. **More recent studies** reflect that the knowledge and awareness of hydrogen increased. Also, the results show that the **public has a positive attitude towards hydrogen fuel technology**, **supports** large scale introduction of hydrogen transportation and are **willing to pay** for its introduction. Also the willingness to **gain more information** about hydrogen, especially amongst young people and women has increased in the last decade.

In the following we've selected and summarized three recent EU funded studies on the public perception and acceptance of hydrogen technology compliment the results of the above-mentioned studies:

Roads2HyCom *(http://www.roads2hy.com/)*

Road2HyCom investigated the public perception and acceptance between 1998 and 2006. They indicate that, in the eyes of the public it is often difficult to separate the use of hydrogen as a fuel, from the fuel cell as a device to turn hydrogen into useful power. Moreover, it is perceived that public opinions about new technologies are based on generic issues such as costs and reliability. However, public's opinion is influenced by the complexity and visibility of the technology. For example, if a technology is not visible or comprehensible for the user, the public opinion is mostly based on whether 'it works or not'. The Roads2HyCom project has studied technical and socio-economic issues associated with the use of Fuel Cells and Hydrogen in a sustainable energy economy, by combining expert studies in technology status, energy supply and socio-economics with an active programme of engagement with key stakeholders, especially early adopters of the technologies. The results of the comprehensive study reflects that currently there is reasonable acceptance of hydrogen and fuel cell

technologies compared to other emerging or advanced fields such as nuclear energy and genetic engineering. The support for hydrogen is generally high, but the knowledge about hydrogen and fuel cells is rather low. Moreover, males and people with higher formal education have a high knowledge on hydrogen technologies than females and people with lower education. There is practically no opposition to the introduction of hydrogen as a fuel and hydrogen vehicles, though many people would like to get more information or do not feel well enough informed. The study indicates that environmental concerns do not play a major role in the short term, but might have a prominent role in the purchase decisions of hydrogen vehicles in the future.

Clean Hydrogen In European Cities – CHIC *(www.chic-project.eu)*

The CHIC project (running since 2010 till the end of 2016) conducted between August 2011 and March 2013 a research on social acceptance of FCH buses and hydrogen technologies. The CHIC research approach has as its starting point the findings of former studies on acceptance indicating a generally positive attitude towards hydrogen and hydrogen technologies in society, but revealing a considerable lack of information/ knowledge on the topic among the general public. The acceptance of FCH buses and hydrogen technologies in the group of stakeholders, responsible for and involved in demonstrating these technologies, had only been partially researched previously. The CHIC research on acceptance aimed at closing this gap and including stakeholders as well as citizens in the research on acceptance of FCH buses in public transport. The overall acceptance of the project initiative and the hydrogen technologies in the group of bus drivers was generally supportive and/or tolerant, but eroding due to the initial bus reliability. However, bus drivers identified significant improvements to the bus characteristics e.g., the driving comfort of the electric drive and the project "vision" convinced people and appeared to make up for set-backs in reliability and performance. The project initiative was clearly supported by the citizens interviewed. They appreciated that "finally somebody is taking action for the environment". However, the awareness about the initiative as well as the potential of the technology was generally low, although the FCH buses had been noticed. The motivation of the people involved in the demonstration of FCH together with the views of the general public as shared in the research interviews revealed the need for further added value other than climate protection in order for these groups to accept fundamental changes in the public transport system.

In addition, the general public trusts in the responsible governmental bodies to not approve anything harmful to health or life, and that they take care that even misuse would not result in any severe damage. The CHIC project also reflects that the general public assumes that any innovation was at least as safe as its existing alternative. This high level of trust in authorities might explain the differences of safety discussions on hydrogen technologies in this research compared to countries outside Europe and might also explain the evident low interest in discussing safety issues.

CreateAcceptance *(http://www.esteem-tool.eu/; www.createacceptance.net)*

The project Create Acceptance (Heiskanen et al, 2007) contributes to facilitating the implementation of new and emerging sustainable energy technologies by assessing optimal conditions for the implementation of these new technologies in terms of socio-economic aspects, consumer preferences

and citizen needs. The objectives of the project are to increase the competitiveness of RES (Renewable Energy Sources) and RUE (Rational Use of Energy) technologies by developing a tool (The Esteem Tool) that can measure, promote and improve social acceptance of these technologies. The EU-funded project *CreateAcceptance* represents an extensive study into the acceptance of specific instance of energy technology. An important finding of the project is that **public acceptance results often from the interaction between a project and its context.** Energy-related projects influence and change the context on which they are operating on, e.g. an hydrogen project might result in lower value of surrounding property. Depending on the nature of the changes and the characteristics of the context, this may lead to local acceptance or resistance of the general public.

On top of the above-mentioned studies and sources, we have assessed other sources of information and studies on public opinion about hydrogen safety, mainly at European level. It should be noted, however, that many studies do not provide a full representative data collection as they e.g. include a limited amount of interviews, are only conducted in specific (large) cities or are not executed according to a scientific framework.

4 Recommendations on public safety of large scale handling and transportation of hydrogen

The objective of the present Report was to conduct a public safety assessment of the large scale handling, transportation and storage of hydrogen. In this paragraph the results and recommendations that have come forward from this safety assessment are summarized.

Public safety of hydrogen

In general hydrogen causes no more safety concerns than other flammable, gaseous fuels, and must be handled equally responsibly. Hydrogen can be handled safely as long as users are familiar with the characteristics of hydrogen and act according to available regulations, codes, standards and guidelines. All fuels have some degree of danger associated with them, and hydrogen is no different although hydrogen has some differing characteristics which require attention. These differences have to be considered during transportation and storage but when taken into account, the public safety risks related to hydrogen are fairly low and are comparable to other gaseous fuels.

An overview of the most common RCS was provided, based on desk research and taking into account the results of interviews and the data gathering exercise in D3.1. Suitable RCS are of importance for the successful market deployment of hydrogen technology. At present hydrogen is mostly covered by more general RCS; few or no specific RCS have been developed for hydrogen at national and/or European level and there are still several improvements to be made, for instance with regard to:

- lack of familiarity of codes and standards on hydrogen among project developers
- incomplete requirements for RCS on high pressure storage, handling and use as well as sensing technologies
- limited harmonization of RCS at national as well as European/international level

The need for improvements is also applicable to the current guidelines on hydrogen as they are mainly focussed on the industrial application of hydrogen. The question is if these industrial guidelines are in all cases suitable or replicable for the use of hydrogen in the public domain. Limited information was found on specific guidelines for the handling, storage and use of hydrogen in the public domain. Projects already conducted in the public area (such as pilot and demonstration projects) could provide input for suitable guidelines and mitigation measures in the public domain, but more structured extraction of valuable information and wider outreach activities are needed to make this happen.

Public perception of hydrogen safety

Public acceptance and their opinion about the safety of hydrogen influence the success of the implementation of hydrogen technologies in transport. As indicated earlier, the safety and risks associated with hydrogen can be considered on an equal level with other flammable, gaseous fuels.

The public opinion on a new technology such as hydrogen however, is the result of a summed evaluation of perceived attributes related to the new technology and the associated benefits, costs and risks. A review of the findings of the recent literature on acceptance, attitudes and preferences for (safety of) hydrogen and fuel cell technologies show a significant increase of the knowledge regarding hydrogen in general and an increase of awareness of hydrogen as a potential alternative fuel technology. Especially people working in the transportation sector believe that hydrogen has the potential to replace conventional fuels in the future. Furthermore, the studies mentioned before showed that the knowledge and awareness of hydrogen increased consistently in the last 10 years and that the public start having a positive attitude towards hydrogen fuel technology, supports large scale introduction of hydrogen transportation and are willing to pay for its introduction. Moreover, the willingness to gain more information about hydrogen, especially amongst young people and women has increased in the last decade. Only one report specifically mentioned safety on national and regional level: it reflects that although hydrogen projects have so far been perceived as safe, the safety of hydrogen is still a topic of concern.

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