EXAMINING THE ROLE OF SAFETY IN COMMUNICATION CONCERNING EMERGING HYDROGEN TECHNOLOGIES BY SELECTED GROUPS OF STAKEHOLDERS

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ABSTRACT

Governments and other stakeholders actively promote and facilitate the development and deployment of hydrogen and fuel cell technologies. Various strategy documents and energy forecasts outline the environmental and societal benefits of the prospective hydrogen economy. At the same time, the safety-related properties of hydrogen imply that it is not straightforward to achieve and document the same level of safety for hydrogen systems, compared to conventional fuels. Severe accidents can have major impact on the development of energy technologies. The stakes will increase significantly as the use of hydrogen shifts from controlled environments in industrial facilities to the public domain, and as the transport-related consumption extends from passenger cars and buses, to trains, ships and airplanes. Widespread deployment of hydrogen as an energy carrier in society will require massive investments. This implies commercial and political commitment, involvement and influence on research priorities and decision-making. The legacy from accidents and the messages communicated by influential stakeholders impact not only how the public perceives hydrogen technologies, but also governmental policies, the development of regulations, codes and standards (RCS), and ultimately the measures adopted for preventing and mitigating accidents. This paper explores whether and how selected aspects of safety are considered when distinct groups of stakeholders frame the hydrogen economy. We assess to what extent the communication is consistent with the current state-of-the-art in hydrogen safety and the contemporary strength of knowledge in risk assessments for hydrogen systems. The approach adopted entails semi-quantitative text analysis and close reading to highlight variations between diverse groups of stakeholders. The results indicate a bias in the framing of the safety-related aspects of the hydrogen economy towards procedural, organisational and societal measures of risk reduction, at the expense of well-known challenges and knowledge gaps associated with the implications of fundamental safety-related properties of hydrogen.

Keywords: *hydrogen economy; hydrogen safety; risk awareness; risk perception; risk acceptance; risk assessment; strength of knowledge; communication; strategy documents.*

1.0 INTRODUCTION

1.1 The role of safety in the hydrogen economy

The Paris Agreement and the Sustainable Development Goals (SDGs) from the United Nations (UN) reflect the realisation that the global energy mix needs a transition towards increased use of renewable energy sources. The variable and intermittent supply of energy from solar and wind points to energy systems where hydrogen or hydrogen-based fuels are the primary energy carriers. Existing technologies can convert energy from renewable or non-renewable sources into hydrogen, hydrogen can be stored and transported in compressed, liquid or chemical form, and energy converters, such as turbines and fuel cells, can deliver electrical or mechanical energy and heat on demand [1-3].

Several national governments and the European Union (EU) have issued ambitious strategies and roadmaps for the deployment of hydrogen technologies, pointing towards the realisation of the hydrogen economy. At the same time, the safety-related properties of hydrogen imply that it is not straightforward to achieve and document the same level of safety for hydrogen systems, compared to conventional fuels. Accidents are unintended and sudden events that result in losses, such as loss of life, material values or reputation, and safety implies control over hazards that can result in losses. Safety engineering aims to reduce or eliminate hazards, and thereby assure that systems are designed and operated within safe boundaries. Best practice in safety engineering entails a hierarchy of principles for risk reduction, starting with inherently safe design, whenever possible, followed by preventive and mitigative measures, and finally procedural safety. In this context, risk is a measure of the expected losses for a specified system or activity, and the purpose of the risk analysis and risk assessment is to support decisions by analysing, documenting and communicating safety knowledge to stakeholders. There is increasing awareness and recognition of the importance of reflecting the knowledge and expressing the uncertainty in the understanding, analysis, assessment and management of risk [4].

Hydrogen is an extremely flammable and highly reactive substance, with low specific density and exceptionally low boiling point. As such, fires and explosions in hydrogen systems represent a hazard to people, industries and society [5-6], and it is not realistic to envisage widespread use of hydrogen as an energy carrier in society unless the stakeholders behind the emerging hydrogen technologies can demonstrate that the associated risk is equivalent to, or preferably lower than, the corresponding risks for conventional energy carriers [7-11]. This represents a significant technological, organisational and societal challenge which must be seen in relation to the strategies for implementation [12].

Risk perception is often expressed as a function of unknown risk and dread risk [13]. Whether decision makers or the public perceive the risk associated with a specific energy carrier as acceptable depends on numerous factors, such as the benefits resulting from the technology; the legacy and lessons learnt from previous accidents; how systems are constructed, maintained and managed; relevant properties of the energy carrier, including toxicity and flammability; public perceptions of hazards, as well as moral or ethical aspects and environmental concerns; the strength of knowledge in risk assessments; and the level of trust in relevant sources of information [14-18]. This paper is concerned with the last point, in particular whether and how distinct groups of influential stakeholders include important aspects of hydrogen safety in their framing of the hydrogen economy.

Given the contemporary interest in hydrogen technologies and the critical importance of safety in energy systems, it is relevant to explore how the role of safety appears in the international discourse on the prospective hydrogen economy. Severe accidents can have major impact on the development of energy technologies, and the stakes will increase significantly as the use of hydrogen shifts from controlled environments in industrial facilities to the public domain, and as the transport-related consumption extends from passenger cars and buses, to trains, ships and airplanes. Awareness and perception of risk in the public and amongst decision makers influence the adoption of hydrogen technologies. While the international discourse tends to focus on the positive implications of the hydrogen economy, such as benefits for the environment and prospects for value creation and economic growth, the implications for safety and risk are less obvious. Discourse analysis and problem framing have been developed across a range of disciplines, particularly within social sciences, as tools for exploring the dominant perspectives in the conceptualization and dissemination of particular themes, technologies or applications. According to Entmant [19]: *'to frame is to select some aspects of a perceived reality and make them more salient in a communicating text, in such a way as to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation for the item described'.* As such, the framing of hydrogen technologies to a broader audience is likely to influence public perception.

1.2 Previous work

Earlier discourse analytical studies on hydrogen have explored dominant and often opposing narratives, with a view to identify their contribution in the evolution of hydrogen and fuel cell technologies. Hultman & Nordlund [20] studied the expectations for fuel cell technologies expressed in newspaper articles and governmental reports in Sweden, the European Union (EU) and the USA during the period 1990-2005. Eames *et al.* [21] investigated the role of the hydrogen economy as a vision for the parallel evolution of technology and society. Several papers describe prospects for the hydrogen economy, often with a comprehensive analysis of the technologies involved in selected parts of the hydrogen value chain [22-25]. Dawood *et al.* [26] investigated the interdependency of four stages of the hydrogen lifecycle, *production*, *storage*, *safety* and *utilisation*, with particular focus on production. Others have focused on technical and commercial barriers for value creation in the hydrogen economy [27-29].

1.3 The present study

This paper examines the role of safety in the international discourse of the hydrogen economy. The aim is to explore whether and how distinct groups of stakeholders include critical aspects of safety in the framing of the hydrogen economy. The approach adopted entails semi-quantitative analysis of published documents at three levels of detail. The first level examines the frequency of specific terms related to safety, compared to terms representative of other aspects of the value chain for hydrogen. The second level entails text analysis, supported by a pre-defined list of guiding questions, to explore whether and how the documents address critical aspects of hydrogen safety. Finally, the third level explores whether the source documents include statements concerning the relative safety of hydrogen systems compared to conventional or alternative energy technologies. The analysis assumes that widespread use of hydrogen in society will be accompanied by a framework for risk management and governance [30].

2.0 MATERIALS AND METHODS

2.1 Selection of documents

Governmental strategies are intended to shape future actions and priorities by fuelling interest and defining common goals and visions [21]. To this end, the analysis focused on the documents listed in Table 1. The selection is limited to documents in English, from EU and selected industrial countries with expressed goals and ambitions for realising the hydrogen economy. The inclusion of several documents from the same government allows for exploring the development over time. Documents outlining the role of hydrogen in a wider context of alternative energy sources were not included.

Table 1. The strategy documents included in the present study.

ID	Country	Year	Type	Ref.
S01	Norway	2020	National strategy	[31]
S02	The Netherlands	2020	National strategy	[32]
S03	Germany	2020	National strategy	[33]
S04	France	2020	National strategy	[34]
S05	Japan	2017	National strategy	[35]
S06	Japan	2019	Strategic roadmap effectuating [35]	[36]
S07	South Korea	2019	National strategy (hydrogen economy roadmap)	[37]
S08	Australia	2019	National strategy	[38]
S09	New Zealand	2019	Vision report (background for a national strategy)	[39]
S10	EU	2003	Vision report	[40]
S11	EU	2020	European strategy	[41]
S12	USA	2002	Vision report	[42]
S13	USA	2002	National strategy	[43]
S14	USA	2006	Strategic program plan (first issued in 2004)	[44]
S15	USA	2011	Strategic program plan	[45]
S16	USA	2020	Strategic program plan – updating/expanding [42-45]	[46]
S17	Canada	2020	National strategy	[47]

2.2 Semi-quantitative content analysis

The first level of analysis focused on estimating the relative frequency of specific terms related to safety, compared to terms representative of other aspects of hydrogen as an energy carrier. Fig. 1 illustrates the simplified model of the hydrogen value chain used in this analysis, where *safety* is considered a cross-cutting topic that transcends *production* (i.e., the transformation of energy sources into hydrogen), *storage and distribution* of hydrogen, and *utilisation* (i.e., the consumption of hydrogen by energy converters such as turbines or fuel cells). Although *regulations, codes and standards* (RCS) and *competence* (including education, training and experience) also can be viewed as cross-cutting topics, both aspects are to a large extent specific to each of the four main elements.

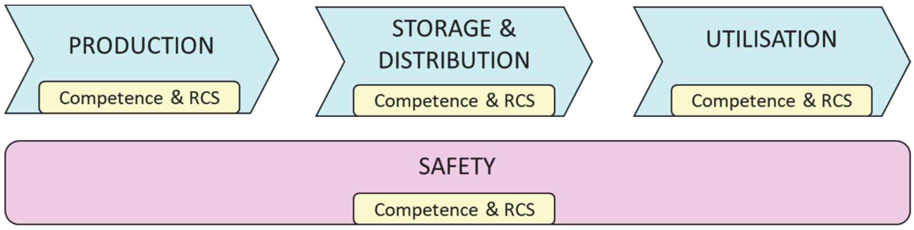
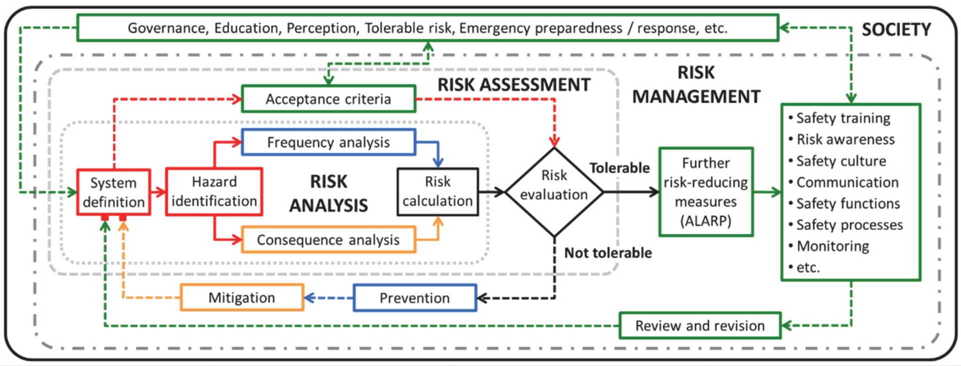


Figure 1. Simplified value chain for hydrogen as an energy carrier.

The analysis of the seventeen documents (S01-S17) listed in Table 1 involved an iterative process using the MaxDictio module in the text analysis software MAXQDA Analytics Pro 2020 (v20.4.0). For consistency, the analysis focused on the core text of the documents, after removing tables of contents, lists of references and abbreviations, glossaries and footnotes. The first step involved an automated search to identify frequently occurring single words, as well as combinations of words. After sorting the identified words and phrases according to the categories defined in Fig. 1, each category was complemented with synonyms, spelling options (UK vs. US), commonly used abbreviations, and specific terms such as ‘ATEX’, ‘loss prevention’, etc. The resulting list of search terms was updated in an iterative process involving automated searches and manual verification of the results (precision, recall, context, etc.). Appendix A summarises the final list of search terms for each of the four categories.

2.3 Semi-quantitative text analysis using qualifying questions

The second level of the analysis entailed close reading of each document, guided by a pre-defined list of questions that address critical aspects of hydrogen safety. The questions cover important aspects of safety engineering, risk analysis, risk assessment, risk management, societal safety, and governance of energy systems. The analysis included five questions in each of the four categories $^{(1)}$*System & hazards*, $^{(2)}$*Frequency & prevention*, $^{(3)}$*Consequence & mitigation*, and $^{(4)}$*Risk management & society*. Fig. 2 illustrates how the four categories relate to essential concepts in hydrogen safety and governance, and Appendix B lists the resulting twenty (4×5) qualifying questions and general comments on background and context. In the semi-quantitative analysis, a document got one point for each positive answer, and zero if the answer was negative.



1. System & hazards	2. Frequency & prevention	3. Consequence & mitigation	4. Risk management & society
1A: Classification	2A: Density/buoyancy	3A: Fire and flame	4A: Governance
1B: Process conditions	2B: Flammable range	3B: Deflagration	4B: Competence
1C: Compatibility	2C: Ignition sensitivity	3C: Detonation	4C: Safety culture
1D: RCS limitations	2D: Prevention	3D: Mitigation	4D: Perception
1E: Inherent safety	2E: Experience	3E: Modelling	4E: Tolerable risk

Figure 2. Schematic of risk-related processes and the four categories of qualifying questions.

2.4 Qualitative framing of hydrogen safety

The third level of the analysis entailed close reading of each source document to identify whether and how the texts include statements concerning the overall safety of hydrogen and hydrogen technologies in relation to conventional or alternative energy technologies, i.e., to what extent do the documents address questions such as *“how safe is hydrogen?”*, or *“is hydrogen technologies more or less safe compared to other energy technologies?”*. This analysis was included to provide insight on the overall view of safety in the framing of the hydrogen economy.

3.0 RESULTS AND DISCUSSION

3.1 Semi-quantitative content analysis

Fig. 3 summarise the results from the automated search conducted for the documents listed in Table 1 and the four categories illustrated in Fig.1, using the search terms listed in Appendix A: *a)* total number of words counted, sorted by category, *b)* number of words counted for each category normalised by the total number of words in the document, and *c)* number of words counted for each category normalised by the total number of words counted. Fig. 3a reveals large variation in the number of counted words between the documents. The relative fractions between the categories change significantly between the documents when the counted words are normalised by the number of words in the documents (Fig. 3b). In the following, the discussion will primarily focus on the normalised results summarised in Fig. 3c.

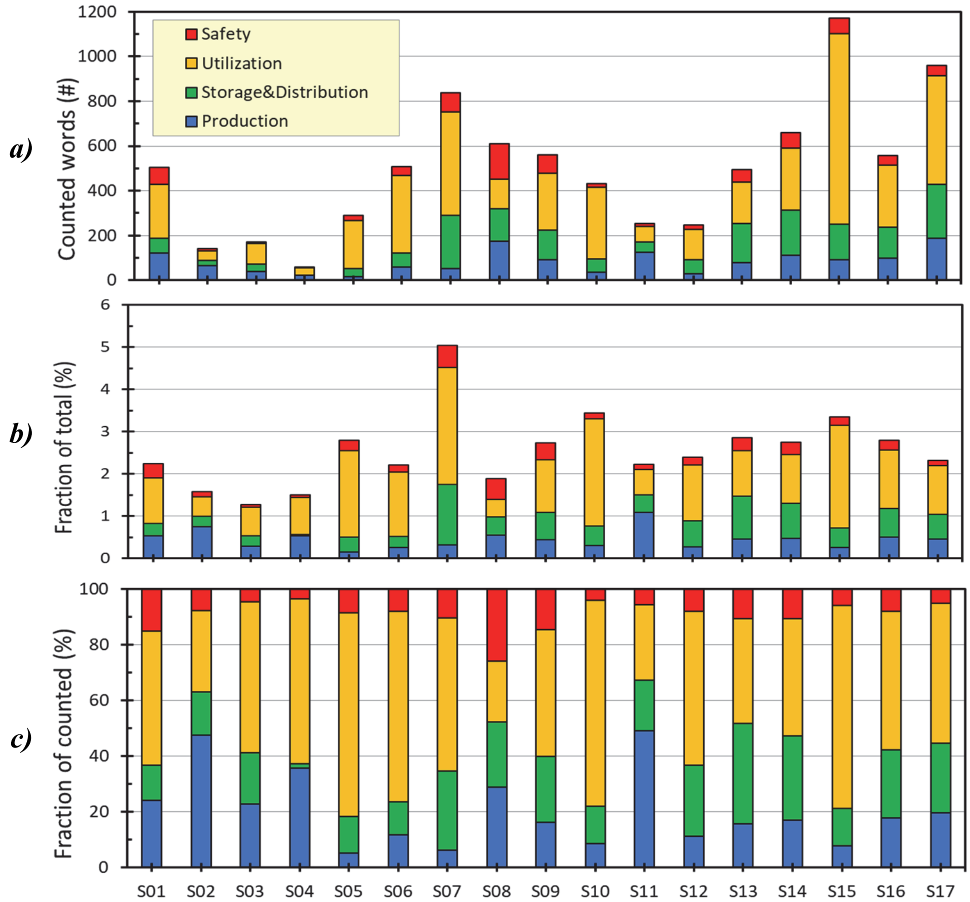


Figure 3. Counted words per category in the seventeen documents (S01-S17) listed in Table 1.

The results illustrated in Fig. 3c reflect that utilisation of hydrogen is the driving narrative in many of the documents, with notable exceptions for the *Netherlands* (S02), *France* (S04), *Australia* (S08) and the *2020 EU strategy* (S11) where production plays a dominant role. A transition in scope and context, from an initial vision featuring applications, towards a strategy for deployment with increased focus on hydrogen production may explain the difference between the European strategies from 2003 (S10) and 2020 (S11). High population densities, energy-intensive industries, and limited natural energy sources may explain the low emphasis on production in the strategies from *Japan* (S05 & S06) and *South Korea* (S07). The historical trend is less obvious for the US strategies (S12-S16), although the development from 2011 (S15) to 2020 (S16) resembles the trend from EU (S10-S11). The documents with the highest normalised score on safety are *Australia* (S08), *New Zealand* (S09) and *Norway* (S01), while *Germany* (S03), *France* (S04) and the *2003 EU Vision report* (S10) occupy the other end of the scale.

The frequency of safety-related terms alone is not an unambiguous measure of the relevant aspects of safety addressed in the documents. Fig. 4 compares the relative fractions of counted words in the safety category, for all non-zero search terms, for five documents. The total scores on safety in the strategy documents for *South Korea* and *Australia* are dominated by the frequent use of the words ‘safe’, ‘safety’ and 'safely", while the distribution in counted words per search terms is much wider for *Norway, Japan* and *New Zealand*. Concerning RCS, which is important for both safety and the deployment of hydrogen technologies, it is worth noting that the search term 'ATEX' gave no hits in any of the documents. This is surprising, given the essential role of the ATEX directives in the European legislation that defines minimum safety requirements for workplaces and equipment for use in explosive atmospheres [48].

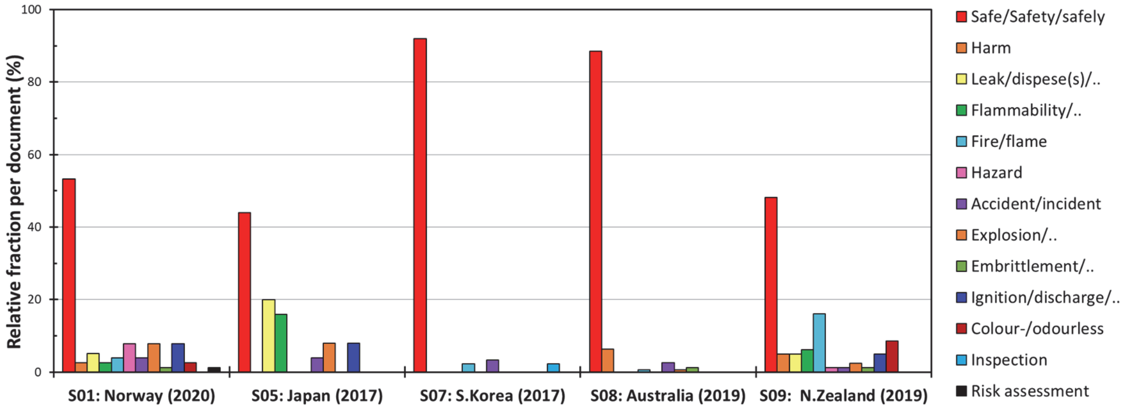


Figure 4. Relative fraction of counted words for all non-zero search terms related to safety.

3.2 Semi-quantitative text analysis using qualifying questions

Fig. 5 summarises the results for each of the seventeen strategy documents (Table 1), for each of the four safety-related categories (Fig. 2), from the semi-quantitative analysis that entailed close reading and assignment of scores based on the twenty qualifying questions summarised in Appendix B.

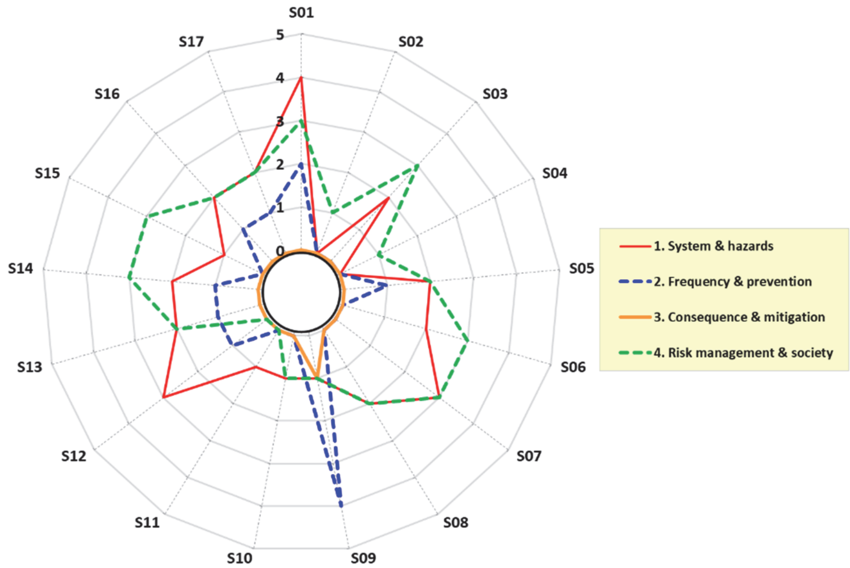


Figure 5. Results from the semi-quantitative text analysis using qualifying questions.

Fig. 6 and Fig. 7 show the distribution of the total scores for each of the seventeen documents listed in Table 1 and each of the twenty sub-categories defined in Fig. 2, respectively. There is significant spread in the results. The strategy documents with the highest total score are *Norway* (S01: 45%), *New Zealand* (S09: 35%), *South Korea* (S07: 30%) and the *US 2006 Strategic Program Plan* (S14: 30%). The scores for *Norway, New Zealand* and *South Korea* are consistent with the distribution of hits by search terms in Fig. 3 and Fig. 4. The strategy documents with the lowest total score are the *Netherlands* (S02: 5%), *France* (S04: 5%) and *EU 2020* (S11: 5%).

The sub-categories with the highest score are *RCS limitations* (1D: 88%), *Competence* (4B: 76%), *Safety culture* (4C: 59%), *Inherent safety* (1E: 41%), *Compatibility* (1C: 41%) and *Governance* (4A: 41%). The sub-categories with the lowest score are *Classification* (1A: 0%), *Tolerable risk* (4E: 0%) and the four sub-categories belonging to *Consequence & mitigation*: *Deflagration* (3B: 0%), *Detonation* (3C:

0%), *Mitigation* (3D: 0%) and *Modelling* (3E: 0%). As such, the overall results show strong focus on procedural, organisational and societal aspects of safety, represented by *RCS limitations* (1D), *Competence* (4B) and *Safety culture* (4C), respectively.

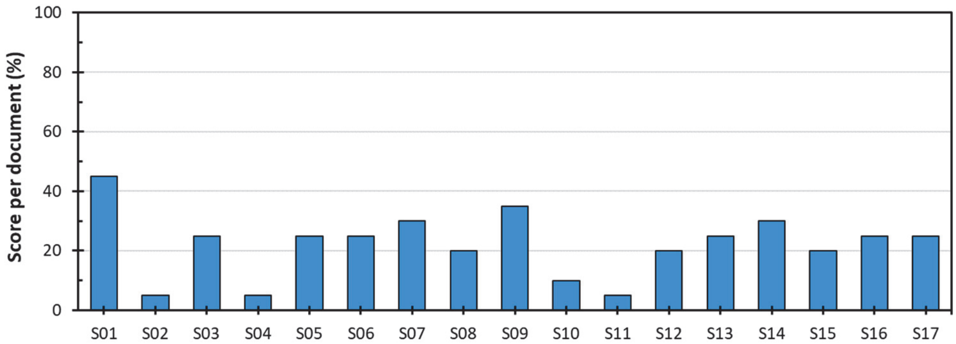


Figure 6. Score per document in the semi-quantitative text analysis using qualifying questions.

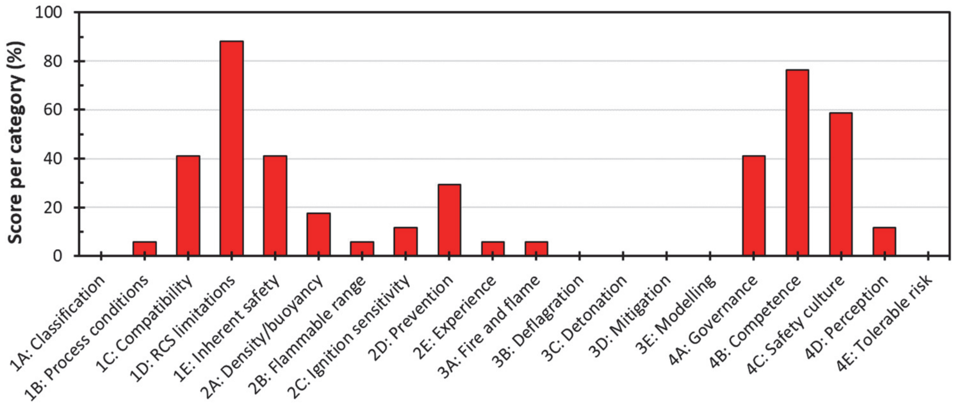


Figure 7. Score per sub-category in the semi-quantitative text analysis using qualifying questions.

3.3 Qualitative framing of hydrogen safety

The final part of the analysis explored whether and how the source documents address the relative safety of hydrogen systems compared to conventional or alternative energy technologies. Table 2 summarises the results, where relevant statements were identified in six of the seventeen documents. Of these, the statements from the *Netherlands* (S02), *South Korea* (S07), *USA* (S13) and *Canada* (S17) express that the safety of hydrogen technologies is similar to that of conventional fuels. Only *Germany* (S03) and *USA* (S12) indicate that extraordinary measures might be required to achieve the required level of safety.

3.4 General discussion

Fig. 8 shows the correlation between the fraction of words counted (Fig. 3c) and the total score from the guiding questions (Fig. 6).

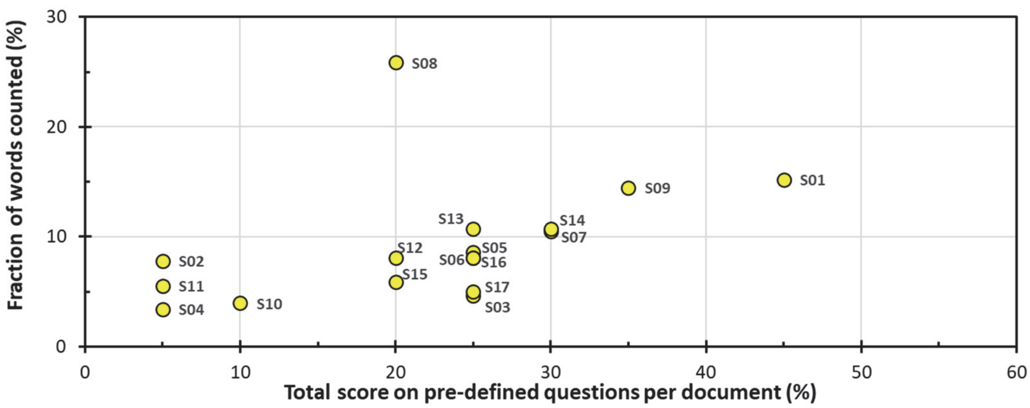


Figure 8. Correlation between the fraction of words counted and the total score on guiding questions.

Table 2. Statements concerning the relative safety of hydrogen compared to conventional fuels.

ID	Country (year)	Statement	Page
S02	Netherlands (2020)	*"At present, the risks of hydrogen are not estimated to exceed the risks of current fossil fuel sources."*	63
S03	Germany (2020)	*"The special physical and chemical properties of hydrogen mean that a robust quality assurance infrastructure for the development and in particular the monitoring of facilities to produce, transport, store and use hydrogen is essential."*	8
S09	New Zealand (2019)	*"Safety considerations similar to natural gas or petroleum"*	20
		"Like other energy carriers, hydrogen requires careful health and safety management when used on a large scale."	34
S12	USA (2002)	*"…,specific upgrades and enhancements will be needed to accommodate the unique features of hydrogen, particularly in storage and distribution."*	14
S13	USA (2002)	*"…:like all fuels, hydrogen can be handled and used safely with appropriate sensing, handling, and engineering measures."*	36
S17	Canada (2020)	*"Similarities between natural gas and hydrogen include their safety considerations, ability to be transported over long distances."*	14

The overall results from the three levels of the analysis are consistent, with a few notable exceptions. Fig. 8 shows that the results for two source documents in particular deviate from the others: *Australia* and *Norway*. For the Norwegian strategy (S01), the inclusion of a separate chapter on hydrogen safety, which covers a broad spectre of safety-related issues, explains the high score from the detailed analysis. The Australian strategy (S08), on the other hand, gets a low score from the close reading and qualification based on guiding questions, while repeated use of the terms 'safe', 'safety' and 'safely" results in a high score from the automated counting analysis (Fig. 3c). The combination of text analysis and the binary outcome of the guiding questions in Appendix B introduces some uncertainty in the analysis. To decide whether a given statement qualified for a positive or negative outcome implied interpretation, and hence subjective judgement. To alleviate the impact of this aspect of the analysis, the evaluation considered the specific context of each statement relative to the questions in Appendix B.

Several documents mention that the hazard associated with hydrogen technologies are under control, or that the risk will be effectively managed through regulatory reforms. Some refer to the experience from industrial use of hydrogen, e.g., the *Green Vision* from New Zealand *(S09, p.26)*:

> *"There are decades of experience of using hydrogen industrially in New Zealand […]. Protocols for safe handling are already in place and exist for hydrogen refuelling infrastructure in site-specific forms."*

However, none of the documents mention that the acceptance criteria for individual risk are about two orders of magnitude lower for members of the public, compared to workers in industrial facilities [49]. As such, it is not straightforward to transform competence, technology and safety culture from industry to society, and from large energy companies where the safety cultures have developed over decades, to smaller start-up companies engaged in the emerging hydrogen technologies.

The lack of emphasis on the consequences of potential accidents suggests that the framing of the hydrogen economy in the national strategies is biased towards virtues of the prospective hydrogen economy, rather than hazards associated with emerging hydrogen technologies. This is not surprising. Nevertheless, considering the considerable investments required for deploying hydrogen technologies in society on a massive scale, and the long-term impact severe accidents can have on the development of hydrogen technologies, the lack of mentioning of well-known and well-documented properties of hydrogen give grounds for concern. Examples of relevant safety-related properties and the associated implications for safety in the present context include [12]:

- The *low density* of hydrogen implies storage and transportation at either high pressures (CH2) or very low temperatures (LH2), and the combination of the extreme process conditions and complex systems imply significant potential for accidents [15,16].
- The extremely low boiling point, and hence *flashpoint*, of hydrogen implies that loss of containment normally will result in the formation of explosive atmospheres [50].

- The extreme *ignition sensitivity* of hydrogen, qualifying for *Gas Group IIC* together with acetylene [51], implies that it is inherently difficult to prevent or control all ignition sources [52].
- The extreme *reactivity* of hydrogen-air mixtures, quantified by the laminar burning velocity [53], implies severe damage potential of explosions in congested and/or confined geometries [54].
- The propensity of hydrogen-air deflagrations to undergo *deflagration-to-detonation-transition* (DDT) under specific conditions represents a severe hazard [55]; research in the aftermath of the Buncefield explosion in 2005 demonstrate the critical importance of considering detonation scenarios in safety engineering and risk assessments for industrial facilities [56].
- The severe *lack of predictive capabilities* of state-of-the-art consequence models for accidental hydrogen explosions, demonstrated in recent blind-prediction benchmark studies [57], represent a significant challenge for safety engineering, as well as a significant source of uncertainty in risk assessments for hydrogen systems.

The extreme properties of hydrogen, combined with the inherent lack of data for event frequencies and the poor predictive capabilities of state-of-the-art consequence models for representative systems result in significant knowledge gaps that cannot be closed solely by procedural, organisational or societal measures. To this end, it can be argued that basic ethical considerations, such as *'the precautionary principle'* and *'the ethics of belief'*, imply that the weak knowledge in risk assessments for hydrogen systems should be emphasised in the framing of the hydrogen economy.

4.0 CONCLUSIONS

This study explored whether and how selected aspects of safety are included in the framing of the hydrogen economy by different strategy documents. The main findings include:

- The framing of particular aspects of hydrogen safety differs significantly between the various documents.
- Although the analysis involves interpretation, and hence personal judgement, the results are fairly consistent for the different approaches, and notable deviations can to a large extent be explained.
- The messages conveyed in different strategy documents are not consistent, but most peculiarities can be explained by the context of the strategy document or national circumstances.
- The framing of the hydrogen economy in the national strategies is biased towards virtues of the prospective hydrogen economy, rather than known hazards associated with emerging hydrogen technologies.

This paper focused on national strategies that outline visions or roadmaps for the hydrogen economy. Further work will focus on developing the methodology further, with a view to extend the analysis to other groups of stakeholders.

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APPENDIX A: SEARCH TERMS

Table 3: Search terms per category in the hydrogen value chain (Fig 1) for the first level of the text analysis. For the sake of brevity, the table presents condensed search terms, without the US spelling options, and with the inclusive OR operator replaced by slash (/).

Production	Storage and distribution	Utilisation	Safety
electrolysis	gaseous hydrogen / GH2	fuel cell / FC	hazard(s) / hazardous
electrolyser(s)	compressed hydrogen / CH2	FCEV	safe / safely / safety
[water] splitting	liquid hydrogen / LH2	car(s) / bus(es) / vehicle(s)	risk analysis
reformer(s)	chemical storage	hybrid	risk assessment
reforming / reformation	liquefaction	forklift(s)	risk management
gasification	liquefied hydrogen	passenger ship / ferry(ies)	loss prevention
steam methane reforming / SMR	solid hydrogen storage	(air)plane(s) / aircraft(s) / aviation	emergency preparedness
pyrolysis	compression	trains	emergency response
polymer electrolyte membrane / PEM	liquid organic hydrogen carrier(s) / LOHC(s)	transport(ation) sector / transport(ation) industry	first responder(s) / emergency responder(s)
partial oxidation [coal]	hydride(s)	heavy duty vehicle(s)	acceptance criteria
biomass conversion	compression	heavy duty transport	risk awareness
biological	hydride(s)	light duty vehicle(s)	flammab(le/ility)
bacterial	organic compound	mobility sector	explosive
bio-hydrogen	[storage] cylinder(s)	smart mobility	embrittle(ment)
central(ised) production	distribute / distribution	heat(ing)	ATEX
decentralised production	dispense / dispenser / dispensing	power generation / electricity generation	National Fire Protection Association / NFPA
distributed production	hydrogen delivery	maritime industry / maritime sector	loss of containment
green hydrogen	delivery system(s)	maritime (hydrogen) applications	leak(s) / leakage(s)
renewable hydrogen	delivery infrastructure	maritime transport(ation)	odourless
blue hydrogen	gas grid / gas network	industry(y/ial) feedstock	colourless
clean hydrogen	gas infrastructure	combustion	disperses / dispersion
grey hydrogen	pipeline(s)	combustor	stratification
turquoise hydrogen	hydrogen tank(s)	synthetic fuel	ignition / discharge
	hydrogen storage	steel production / making	flame / fire
	transmission	refining / refining sector	inspection
	(re)fuelling station(s) / filling station(s) / HRS	transport(ation) applications	incident / accident
	(re)fuel(ing)	chemical industry	explode / explosion
	carrier ship		shock wave / blast wave
			injury(ies) / harm
			fatalities / loss of life

APPENDIX B: GUIDING QUESTIONS

Table 4: Search questions per category in the classification of hydrogen safety (Fig 2) for the second level of the text analysis.

Category	Question	Comments and context
1. System & hazards		
1A **Classification**	*Does the document mention any differences in intrinsic hazardous properties between hydrogen and other energy carriers widely used in society?*	This question focuses on the formal classifications of materials and equipment in relevant RCS[1].
1B **Process conditions**	*Does the document mention any safety-related implications of high pressures (CH2) or low temperatures (LH2) in hydrogen energy systems?*	The low energy density implies that hydrogen typically is stored and distributed at higher pressures or significantly lower temperatures than other energy carriers.
1C **Compatibility**	*Does the document mention any implications of the unique properties of the hydrogen atom or molecule concerning the compatibility of materials or components with hydrogen applications?*	This question focuses on hydrogen diffusion in materials, including molecular diffusion (slow leaks) and embrittlement.
1D **RCS limitations**	*Does the document mention any need for developing or updating specific RCS to facilitate or support safe deployment and operation of hydrogen energy systems?*	This question focuses on shortcomings in existing RCS[2].
1E **Inherent safety**	*Does the document mention the possibility of eliminating or reducing hazards in hydrogen systems by inherently safe design?*	The concept of inherently safe design entails the four principles: minimisation, substitution, moderation and simplification.
2. Frequency analysis & prevention		
2A **Density / buoyancy**	*Does the document mention any implications for safety of the low density of hydrogen relative to air at the same temperature and pressure?*	The low specific density of gaseous hydrogen implies that low-momentum releases will form buoyant plumes.
2B **Flammable range**	*Does the document mention any implications for safety of the wide flammable range of hydrogen-air mixtures compared to other fuels?*	Hydrogen air mixtures can be ignited over a wider range of concentrations, compared to most other energy carriers.
2C **Ignition sensitivity**	*Does the document mention that the energy required for igniting hydrogen-air mixtures is significantly lower compared to other fuels?*	This implies that hydrogen can be ignited by ignition sources that normally would not be able to ignite conventional fuels.
2D **Prevention**	*Does the document mention any specific requirements or challenges related to preventive measures for hydrogen systems?*	The focus is on conventional preventive measures, apart from inherently safe design (1E).
2E **Experience**	*Does the document mention any implications of the inherent lack of experience with emerging hydrogen technologies for safety engineering or risk assessments?*	The lack of relevant data from accidents and incidents introduces significant uncertainty in risk assessments.

[1] Relevant RCS that specify hazardous materials and requirements for equipment intended for use in hazardous areas include:
- United Nations (UN): GHS *"Globally harmonized system of classification and labelling of chemicals"*.
- National Fire Protection Association (NFPA): NFPA 704 *"Standard system for the identification of the hazards of materials for emergency response"*.
- International Electrotechnical Commission (IEC): IEC 60079-0:2017 *"Explosive atmospheres, Part 0: Equipment, General requirements"*.

[2] Examples of relevant limitations in existing RCS include:
- International Maritime Organisation (IMO): IGF Code *"International code of safety for ships using gases or other low flash point fuels"* does not include specific functional requirements for hydrogen.
- European Committee for Standardization (CEN): EN 14994:2007 *"Gas explosion venting protective systems"* is not applicable for hydrogen due to the high reactivity of hydrogen-air mixtures.

Category	Question	Comments and context
3. Consequence analysis & mitigation		
3A **Fire and flame**	*Does the document mention any specific issues with hydrogen fires that may have implications for safety?*	Pure hydrogen burns with a near invisible flame, and hydrogen fires emit less radiation compared to hydrocarbon fires.
3B **Deflagration**	*Does the document mention any implications of the extreme reactivity of hydrogen compared to other relevant energy carriers?*	In general, the higher reactivity implies more severe consequences in explosion accidents.
3C **Detonation**	*Does the document mention that hydrogen-air mixtures may undergo deflagration-to-detonation-transition (DDT) under specific conditions?*	Extensive research over the last decade has demonstrated the critical importance of considering detonations in risk assessments.
3D **Mitigation**	*Does the document mention that conventional methods for mitigating the effect of fires and explosions may have limited applicability for hydrogen?*	The extreme reactivity of hydrogen-air mixtures implies that measures such as deflagration venting and suppression has limited applicability in practice.
3E **Modelling**	*Does the document mention that conventional consequence models have limited predictive capabilities for hydrogen explosions?*	The inherent lack of predictive capabilities of advanced consequence models implies that it is not straightforward to quantify risk or to optimise design solutions.
4. Risk management & societal risk		
4A **Governance**	*Does the document mention any specific requirements concerning the management of safety and risk in the workplace that follow from national or international legislation?*	This question focuses on specific legislation that owners and operators of hydrogen facilities are legally obliged to comply with[3].
4B **Competence**	*Does the document mention the importance of education and training for safe deployment and use of hydrogen in organisations and society?*	Competence is a prerequisite for informed decisions concerning the safe deployment and operation of hydrogen facilities.
4C **Safety culture**	*Does the document mention the importance of safety culture or other aspects of risk management for safe operation of hydrogen facilities?*	In this context, other relevant aspects of risk management include risk communication, risk awareness, lessons learnt, procedural safety and emergency preparedness.
4D **Perception**	*Does the document mention the possible implications severe accidents can have on public perception and further development and deployment of hydrogen technologies?*	Severe accidents, such as Titanic, Hindenburg, Flixborough, Three Mile Island, Bhopal, Chernobyl, Piper Alpha, Buncefield and Fukushima Daiichi, can have severe impact on the development of technology, RCS and public perception.
4E **Tolerable risk**	*Does the document mention the significant difference in acceptance criteria between industrial facilities and the public domain?*	The upper thresholds for individual risk are typically 10^{-3}-10^{-4} and 10^{-5}-10^{-6} fatalities per year for workers in industrial facilities and members of the public, respectively.

[3] Relevant examples of relevant regulatory frameworks in Europe include the ATEX workplace directive (1999/92/EC), the ATEX equipment directive (2014/34/EU), the SEVESO directive (2012/18/EU), and the pressure equipment directive (2014/68/EU).