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The Role of Safety in the Framing of the Hydrogen Economy by Selected Groups of Stakeholders

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While the international discourse on the hydrogen economy tends to focus on the importance of enabling the transition from fossil to renewable energy sources and the prospects for innovation and value creation, the communication concerning the implications for safety and risk is less consistent and often ambiguous. The safety-related properties of hydrogen imply that it is not straightforward to achieve the same level of safety for hydrogen systems, compared to similar systems using conventional fuels. Considering the long-term impact severe accidents may have on public perception, and the deployment of hydrogen technologies in society, the present study explores the framing of hydrogen safety by key stakeholders in the hydrogen ecosystem. This paper focuses on strategy documents published by selected intergovernmental organisations (IGOs), public private partnerships (PPPs), and other organisations engaged in the emerging hydrogen technologies. The methodology entails text analysis supported by a list of qualifying questions, following an approach developed as part of a previous study on national strategies. Compared to the results obtained for the national strategies, the framing of hydrogen safety by IGOs and PPPs is more diverse: the messages conveyed reflect the missions and visions of the organisations, and hence the context in which the source documents were produced. Furthermore, there is alarmingly low emphasis on vital aspects of hydrogen safety in the industry-driven roadmaps and policy guides. The overall results indicate a consistent lack of emphasis on the consequences of accidents and a persistent bias towards procedural and organisational measures of risk reduction.

1. Introduction

There is growing interest in hydrogen as a clean and versatile energy carrier: existing technologies can convert energy from renewable or non-renewable sources into hydrogen, hydrogen can be stored and distributed in compressed, liquid or chemical form, and energy converters such as fuel cells and turbines can deliver electrical or mechanical energy and heat on demand. At the same time, many hydrogen systems entail emerging technologies, and hydrogen is the most reactive and easily ignitable of all energy carriers ever considered for widespread use in society. As such, it is not straightforward to achieve and document an equivalent level of safety for hydrogen systems, compared to similar systems based on conventional fuels (Skjold, 2020).

The ambitions to facilitate widespread use of hydrogen as an energy carrier in industry and society are reflected in strategy documents from national governments, intergovernmental organisations (IGOs), public private partnerships (PPPs) and other stakeholders. The messages communicated in such documents are likely to influence priorities in research and policy, the development of regulations, codes and standards (RCS), the perception and awareness of risk, and ultimately the measures adopted for preventing and mitigating accidents. To this end, Derempouka et al. (2020) explored how the role of safety is outlined in 17 strategy documents published by selected national governments and the European Union (EU). The present study extends this analysis to address documents published by specific IGOs, PPPs and other interest groups. The aim is to explore whether influential stakeholders include vital aspects of hydrogen safety in their framing of the hydrogen economy and to what extent the content is in line with the state-of-the-art in hydrogen safety.

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2. Materials and methodology

Derempouka et al. (2020) describe the methodological framework in detail. The following sections outline the selection of source material for the present study and specific aspects dictated by the context of the documents.

2.1 Material selection

The selection of source documents focused on recent publications from geographically distributed organisations that play an active role in facilitating and monitoring the deployment of hydrogen technologies. A first screening produced 27 documents published in the period 2017-2021. From this selection, documents explicitly excluding or targeting safety were not included for further assessment, with one exception: the latest report from the Research Priority Workshop (RPW) organised by the International Association for Hydrogen Safety (HySafe) was included to benchmark the methodology against the contemporary state-of-the-art in hydrogen safety. Table 1 lists the selected documents, sorted by category: (i) organisations representing the maritime or aviation sectors (D01-D04); (ii) global institutions that drive collaboration on innovation, policy and RCS (D05-D08); and (iii) relevant industrial coalitions, PPPs and associations (D09-D14).

Table 1: Source documents included in the present study.

ID	Type	Target-sector /context	Reference
D01	Report	Aviation	ACI and ATI (2021)
D02	Report	Aviation	McKinsey & Company (2021)
D03	Whitepaper	Maritime sector	ABS (2021)
D04	Outlook	Maritime sector	DNV (2021)
D05	Policy guide	Entire value chain: near term action	IEA (2019)
D06	Policy guide	Entire value chain: deployment acceleration	IEA (2021)
D07	Policy guide	Supply chain: supply economics & barriers	IRENA (2019)
D08	Policy guide	Supply chain: upstream/midstream	IRENA (2021)
D09	Policy paper	Maritime sector	Hydrogen Europe (2021)
D10	Roadmap	Road transport sector (buses)	CaFCP (2019)
D11	Roadmap	Entire value chain	FCHEA (2021)
D12	Roadmap	Entire value chain	FCH 2 JU (2020)
D13	Roadmap	Entire value chain	Hydrogen Council (2017)
D14	Research report	Hydrogen safety	Azkarate et al., (2020)

2.2 Methodology

The analysis of the national strategies in the previous study entailed three levels (Derempouka et al., 2020). However, since some of the source documents in the present study only target selected aspects of the hydrogen value chain, the analysis of word frequencies exploring the prioritisation of safety relative to other aspects of the value chain, determined from automated text analysis, was deemed less relevant. Hence, the present study comprises only two levels: (i) a semiquantitative analysis of the content of the documents supported by a list of guiding questions, and (ii) close reading to explore to what extent the documents express an opinion on whether hydrogen technologies are more or less safe compared to other energy technologies.

The Appendix summarises the twenty questions used in the semiquantitative analysis. The questions are classified according to four categories, with five questions in each, reflecting selected aspects of risk assessment, risk management and governance for energy systems: (1) System & hazards, (2) Frequency & prevention, (3) Consequence & mitigation, and (4) Risk management & society (Derempouka et al., 2020). For instance, the first question in the first category (1A) explores whether the source documents mention any differences between hydrogen and conventional energy carriers concerning specific hazardous properties governing the classification of fuels (and chemicals) into classes or groups. Each document is assigned one (1) point for each positive answer and zero (0) points if the answer is negative, resulting in a total score in the range 0-5 for each of the four categories, and maximum 20 points in total.

The second level of the analysis entails close reading to determine whether the source documents express an opinion concerning the relative safety of hydrogen as an energy carrier, compared to conventional fuels. Safety implies control over hazards that can result in losses such as material damage, fatalities and injury to people. The purpose of risk assessments is to increase the knowledge about systems or activities, and support decisions that may entail difficult economic, ethical or political deliberations. To this end, it is important to scrutinise the scientific rigor behind statements or arguments by different stakeholders concerning the safety and risk of the emerging hydrogen technologies.

3. Results and discussion

The following sections present and discuss the results of the analysis, including a comparison to the findings in the previous study of national strategies (Derempouka et al., 2020).

3.1 Framing of hydrogen safety

Figure 1 summarises the results from the semiquantitative analysis of the documents listed in Table 1, for each of the four categories. The results show large variation between the various documents and categories. The high scores for the report from the RPW organised by IA HySafe (D14) indicate high relevance of the guiding questions. The scores for the joint report (D01) published by the Airport Council International (ACI) and the Airport Technology institute (ATI), as well as the joint report (D02) from the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) and the Clean Sky 2 Joint Undertaking (CS 2 JU), reflect the crucial importance of safety in aviation. Similarly, the score for the whitepaper (D03) from the American Bureau of Shipping (ABS), reflect similar considerations for the maritime sector. The lower score for the energy outlook (D04) from DNV can likely be explained by the broader scope of this document, compared to the whitepaper from ABS. The overall scores for the remaining documents are low, even if policy documents from organisations such as the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) score reasonably well in Category 1 (Systems & hazards).

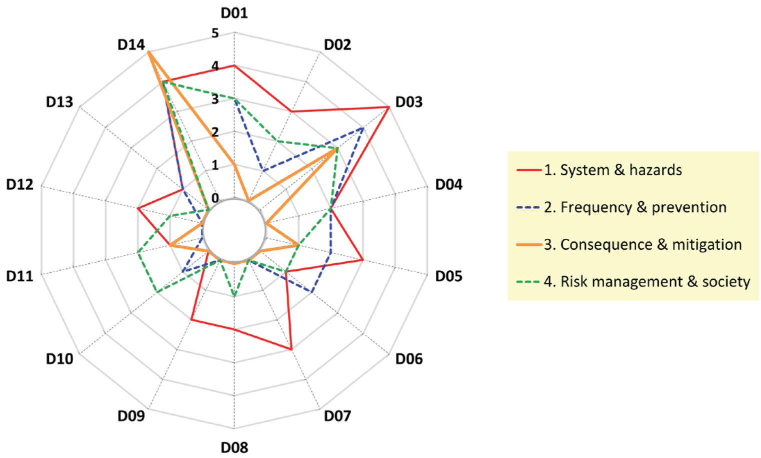

Figure 1: Results from the semiquantitative content analysis of the 14 documents D01-D14 in Table1.

Figure 2 compares the scores per sub-category for the present study, with (blue bars) or without (green bars) the results from the HySafe RPW report (D14), and the previous study on national strategies (red bars). Although there are some notable differences, e.g. for material compatibility and competence building, the overall framing of safety is similar: there is a clear tendency to focus on material compatibility (1C), RCS (1D), competence building (4B) and safety culture (4C), and very limited focus on the challenges that entail complex physical phenomena in Category 3: deflagrations (3B), deflagration-to-detonation-transition (DDT) and detonations (3C), mitigative measures (3D) and the predictive capabilities of consequence models (3E). Several documents in both studies mention the importance of inherently safe design (1E) and preventive measures (2D).

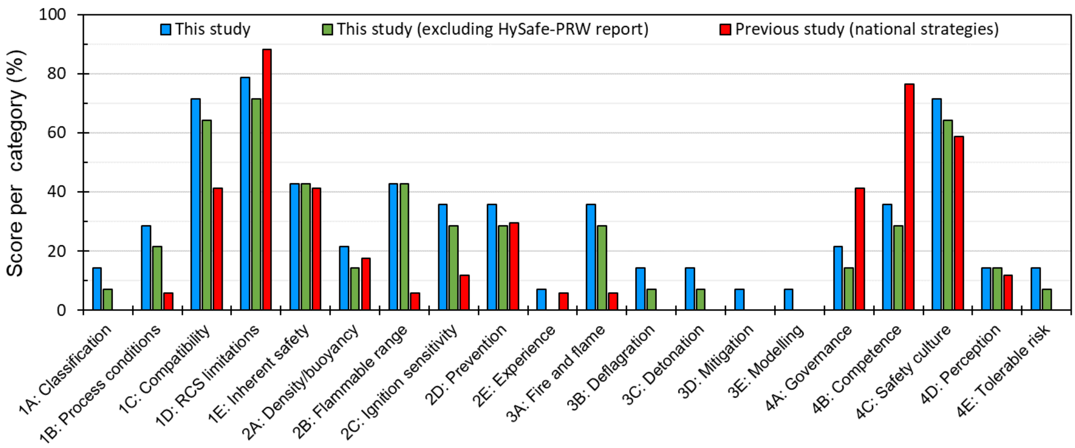

Figure 2: Score per sub-category in the semiquantitative content analysis.

3.2 On the relative safety of hydrogen

Table 2 lists the statements identified in the 14 documents listed in Table 1 concerning the relative safety of hydrogen compared to conventional fuels. Four documents express special concerns for hydrogen: ACI & ATI (D01) and FCH 2 JU & CS 2 JU (D02) mention that the unique properties of hydrogen imply challenges for aviation, and DNV (D04) and IEA (D06) point to specific knowledge gaps for liquefied hydrogen (LH2). Three documents indicate that the level of safety is similar: IEA (D06), IRENA (D08) and FCHEA (D13). Only CaFCP (D10) states that hydrogen is as safe or safer than conventional energy carriers.

Table 2: Statements concerning the overall or relative safety of hydrogen identified in the source documents.

ID	Group	Statement	Page
D01	ACI & ATI	"Hydrogen fires exhibit a very different behaviour compared to Jet A-1 fires and as such present different hazards"	13
D02	FCH 2 JU & CS 2 JU	"… new regulations will need to be developed to ensure adequate and safe handling of low temperature LH2 and its unique properties […] safety considerations are still highly preliminary and need to be refined through further research"	45
D04	DNV	"The general understanding of hazards and risk associated with hydrogen, and particularly liquefied hydrogen (LH2), is limited."	36
D06	IEA	"… the project [Hy4Heat] found that 100% hydrogen use is as safe as natural gas for heating and cooking"	91
		"… a significant lack of understanding regarding the accidental behaviour of liquid hydrogen was identified as an outstanding challenge"	40
D08	IRENA	"Hydrogen can be as safe as the fuels in use today, with proper handling and controls"	22
D10	CaFCP	"The safety of hydrogen as a fuel already meets or exceeds that of natural gas and liquid petroleum fuels"	12
D11	FCHEA	"… hydrogen is an invisible, odorless, flammable gas, and like any chemical or fuel, it requires sound safety measures"	21

3.3 General discussion

Figure 3 summarises the total scores from the semiquantitative analysis of the 14 documents listed in Table 1. As mentioned above, the report from the RPW organised by HySafe achieved the highest score (D14), confirming the relevance of the guiding questions listed in the Appendix. Furthermore, the scores obtained by ACI & ATI (D01) and ABS (D03) are consistent with the emphasis on safety by stakeholders in aviation and shipping. Both sectors are characterized by autonomous systems of high complexity, large potential for severe losses in single accidents (especially for passenger vessels), in addition to mature safety standards and strong safety cultures that have been developed over decades. It is important to consider safe evacuation of passengers and crew, as well as the limited applicability of conventional measures for explosion protection, such as deflagration venting, active suppression or isolation, fire and blast walls, and safety gaps. Airlines in particular are widely regarded High Reliability Organizations (HROs), i.e. organizations that succeeded in avoiding catastrophic accidents in environments where accidents can be expected due to risk factors and complexity. HROs tend to emphasise the five principles of collective mindfulness: (1) preoccupation with failure, (2) sensitivity to operations, (3) reluctance to simplify (4), commitment to resilience, and (5) deference to expertise. Similarly, the collective experience and coordinated efforts from the International Maritime Organisation (IMO), Flag states and classification societies imply high focus on safety in the maritime sector.

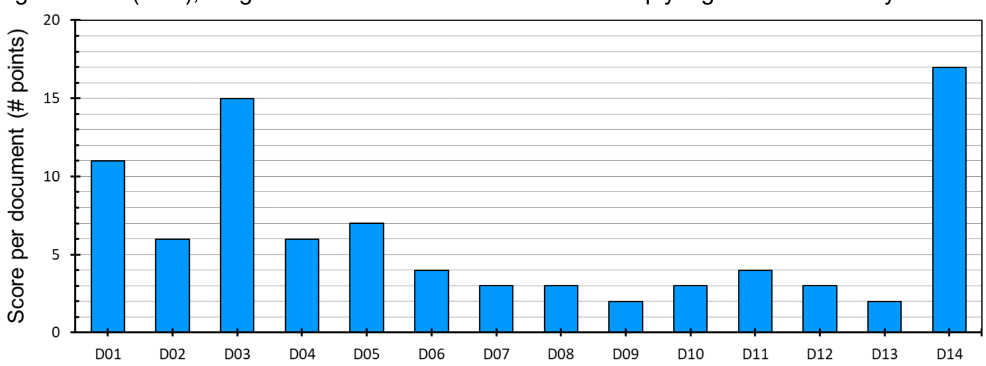

Figure 3: Total score on safety from the semiquantitative content analysis for the 14 documents.

The low scores for the remaining documents give rise for concerns regarding the framing of safety in the international discourse on the hydrogen economy. Although it may not be obvious that safety should be emphasised in all strategy or roadmap documents on hydrogen, it is clear that widespread deployment of hydrogen technologies in society will require massive investments. This implies commercial and political commitment and involvement, and hence influence on research priorities and decision-making. The prospects of severe accidents represent a significant risk to all stakeholders, and the stakes with respect to the potential for severe losses will increase dramatically as the use of hydrogen shifts from controlled environments in industrial facilities to the public domain, encompassing applications such as buses, ferries and airplanes.

Overall, the framing of safety by the various source documents reflects the visions and missions of the respective organisations, and hence the context in which the documents have been produced. Similar to the results obtained for the national strategy documents (Derempouka et al., 2020), there is a general lack of emphasis in the consequences of potential accidents and a persistent bias towards procedural and organisational means of risk reduction. With exception the report from the RPW organised by HySafe, none of the documents mention any implications of the inherent lack of relevant experience data from the emerging hydrogen technologies, despite the obvious need for realistic estimates of event frequencies as input to quantitative risk assessments (Azkarate et al., 2020).

The approach adopted for the semiquantitative analysis entails some uncertainty. The assignment of a binary outcome to each of the guiding questions entailed a certain degree of subjective assessment. To alleviate the impact of this aspect, the evaluation considered the specific context of the statements relative to the intended safety aspect represented by each of the 20 questions.

4. Conclusions

This study examined the role of safety in the framing of the hydrogen economy by selected stakeholders and compared the results to those obtained in a previous study on national strategies. The main conclusions are:

- The framing of hydrogen safety in the source documents reflects the vision and mission of the respective organisations.
- The statements concerning specific challenges in the area of hydrogen safety focus on societal and procedural measures of risk reduction.
- The stakeholders associated with the aviation and maritime industries are most concerned about the safety of hydrogen systems.

5. Suggestions for further work

The analysis of the role of safety in the framing of the hydrogen economy can be extended to additional stakeholders and a broader and updated selection of source documents. It can also be interesting to elaborate on and revise the criteria for selecting source documents and to explore a more sophisticated approach for assessing to what extent the source documents address the guiding questions.

Hydrogen safety is an active area of research with major knowledge gaps (Azkarate et al., 2020; Skjold, 2020). Contemporary research in this area tends to focus on particular applications, explored within conventional disciplines and often supported by experiments performed at laboratory scale, with the presumed outcome of widespread use of hydrogen in society. Whereas conventional approaches treat risk as expectation values, there is increasing awareness of the importance of uncertainty and strength of knowledge (SoK) in risk assessments. Following Aven (2013), the SoK is considered 'weak' if one or more of the following conditions are true: (1) the assumptions made represent strong simplifications; (2) data are not available, or are unreliable; (3) there is lack of agreement or consensus among experts; and (4) the phenomena involved are not well understood, or models are non-existent or known/believed to give poor predictions. To this end, the analysis of the framing of the hydrogen economy can be combined with a critical evaluation of the SoK in risk assessments for hydrogen systems, in general as well as for particular applications.

Finally, the results indicate a potential connection between the concept of collective mindfulness and the level of precision in the framing of hydrogen safety that should be further examined.

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APPENDIX: Categories and guiding questions for the semiquantitative analysis

Category	"Does the document mention … ?	Category	"Does the document mention … ?
1. Systems & hazards:		*2. Frequency analysis & prevention:*	
1A. Classification	… any differences in hazardous properties between hydrogen and other energy carriers?	*2A. Density / buoyancy*	… any implications for safety of the low density of hydrogen relative to air at the same temperature and pressure?
1B. Process conditions	… safety-related implications of high pressures (CH2) or low temperatures (LH2) in hydrogen energy systems?	*2B. Flammable range*	…any safety implications of the wide flammable range of hydrogen-air mixtures relative to other fuels?
1C. Compatibility	… any issues concerning the compatibility of materials or components?	*2C. Ignition sensitivity*	…that the energy required for igniting hydrogen-air mixtures is critically lower relative to other fuels?
1D. RCS limitations	… any need to develop/update RCS to facilitate safe deployment & operation of hydrogen systems?	*2D. Prevention*	…any specific requirements or challenges related to preventive measures for hydrogen systems?
1E. Inherent safety	… the possibility of eliminating or reducing hazards with inherently safe design?	*2E. Experience*	…any implications of the lack of experience with emerging hydrogen technologies for safety engineering or risk assessments?
3. Consequence analysis & mitigation:		*4. Risk management & society:*	
3A. Fire & flame	…any specific safety-related issues with hydrogen fires, compared to hydrocarbons?	*4A. Governance*	… specific requirements concerning safety and risk management in workplace following from national/international legislation?
3B. Deflagration	…any implications of the extreme reactivity of hydrogen compared to other energy carriers?	*4B. Competence*	…the importance of education and training for safe deployment of hydrogen in society?
3C. Detonation	… the propensity of hydrogen-air mixtures to undergo deflagration-to-detonation-transition (DDT)?	*4C. Safety culture*	… the importance of safety culture or other aspects of risk management for safe operation of hydrogen facilities?
3D. Mitigation	… inherent limitations in conventional methods for mitigating the effect of fires and explosions?	*4D. Perception*	… the potential implications of severe accidents on public perception and further deployment of hydrogen technologies?
3E. Modelling	… that conventional consequence prediction models have limited capabilities for hydrogen explosions?	*4E. Tolerable risk*	… the significant difference in acceptance criteria between industrial facilities (incl. maritime) and the public domain?