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A Comparative Assessment of the Inherent Safety of Hydrogen-Fuelled Power Systems

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The utilisation on a large-scale basis of more sustainable solutions for the transport sector represents an essential step to comply with international standards and regulations as well as to reduce the impacts of human activities on the environment. Considering the current global emissions, the development and implementation of innovative solutions allowing for decarbonisation is particularly relevant for maritime transport. Recent studies have indicated the use of hydrogen as a promising solution from medium- and long-term perspectives. For these reasons, this work analyses possible alternative solutions suitable for large-scale ship propulsion based on hydrogen conversion. Considering the current readiness level, available know-how, and training, the use of highly reactive species such as hydrogen poses significant concerns on the safety aspects. Therefore, particular emphasis was given to the quantification of the most relevant safety aspects related to storage, fuel conditioning items, and power production systems. Quite obviously, the possible resulting scenarios are strongly affected by the selected strategy for storing hydrogen, requiring specific studies on the subject. Hence, compressed hydrogen, liquefied hydrogen, and cryo-compressed liquid hydrogen were deeply discussed in this study. For the sake of completeness, the results obtained were compared with data deriving from an existing system based on liquefied natural gas (LNG). Results showed that storage tanks represent the most safety-critical units for all the investigated alternatives evaluated in the analysis, regardless of the inherent safety metric adopted. The inherent safety footprint quantification highlighted that the adoption of emerging technologies based on cryo-compressed liquid hydrogen could improve the onboard inherent safety performance of the ship power system compared to LNG-fuelled engines.

1. Introduction

The transport sector emerges as the third greatest contributor to greenhouse gas emissions worldwide (IEA, 2023). Reducing the carbon footprint of the mobility industry is therefore essential to reach net zero by 2050 (IEA, 2021). In this context, maritime transport represents an important target for decarbonisation, accounting for almost 3 % of global CO_2 emissions (IMO, 2021). Up to now, carbon emissions reduction strategies for maritime technologies have mostly focused on enhancing energy efficiency (IMO, 2019). The large-scale adoption of alternative cleaner marine fuels is expected to contribute significantly to filling the 2050 emission reduction gap left uncovered by energy efficiency measures (Xing et al., 2021).

Liquefied Natural Gas (LNG) is widely recognised as an effective transition fuel, leading to a CO_2 emission reduction of up to 25 % compared to fuel oil-based engines (Iannaccone et al., 2020). Established LNG-based ship power systems typically implement lean burn spark-ignited (LBSI) engines where the gaseous fuel is burned with significant air excess (Iannaccone et al., 2020). However, the overall sustainability of LNG as marine fuel could be greatly penalised by greenhouse effects if methane slips along the fuel value chain are not properly accounted for (Gilbert et al., 2018). Hydrogen-based ship power systems have recently started gaining momentum, mainly due to the possibility of avoiding CO_2 emissions upon combustion. Alternative

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storage concepts, based on compressed gaseous hydrogen, liquid hydrogen, and cryo-compressed hydrogen, can be considered to retain pure hydrogen onboard ships (Baetcke and Kaltschmitt, 2018), with obvious implications on the requirements for fuel conditioning units to be used to make the hydrogen stream suitable for ship propulsion. Concerning its usage, proton exchange membrane fuel cell (PEMFC) technology is often indicated for highly efficient chemical-to-electrical energy conversion, showing large effectiveness especially in the case of small variations of required power in time (van Biert et al., 2016).

Despite the clear environmental benefits, the significant safety concerns related to the use of large quantities of hydrogen tend to hamper its large-scale adoption as a marine fuel because of its low ignition energy, high flame speed, and wide flammability range (Zanobetti et al., 2023a). Most of the available studies have been focused on the assessment of the consequence and frequency of a possible release of hydrogen at storage conditions (Carboni et al., 2022), with a specific focus on the cryogenic liquid case (Ustolin et al., 2022). Conversely, limited knowledge has been developed for the evaluation of combined and intermediate conditions representative of ancillary equipment items required as fuel conditioning units (Salzano et al., 2020).

In this sense, *ex-ante* safety quantification tools for hydrogen-based ship power systems are needed to minimise inherent hazards since early design phases (e.g., technology development and conceptual design), thus leading to enhanced societal acceptability. This study aims to contribute to this research area by developing a structured inherent safety assessment method to rank alternative hydrogen-based ship power systems. For the sake of comparison, an LNG-based ship engine is considered as a baseline in the analysis.

2. Methodology

In this work, a structured procedure consisting of 6 steps was implemented for safety level assessment at an early design stage, considering a case study relevant to maritime transportation. The presented methodology can be intended as an expansion of the strategy previously proposed by the same authors for the evaluation of inherent safety key performance indicators (IS-KPIs) targeting cleaner marine fuels (Zanobetti et al., 2023b). Indeed, an inherent safety footprint quantification is introduced to summarise the overall hazard level of ship power systems. The step-by-step procedure adopted for inherent safety assessment of hydrogen-fuelled ship power systems is outlined in Figure 1 and described in detail below.

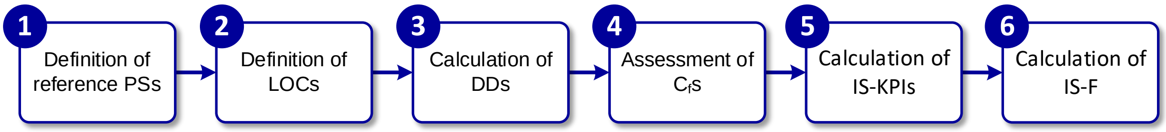

Figure 1: Flow chart of the method developed for inherent safety assessment of hydrogen-based ship power systems

As a Step 1, reference power systems (PSs) are specified in terms of fuel storage-to-utilisation process steps and corresponding operating conditions as well as the preliminary design of constituting process and storage units. The alternative PSs considered in the analysis are defined in the following section. Then, in Step 2, the following set of loss of containment events (LOCs) is considered for units characterising the specified PSs: R1 (small leak – continuous release from a 10 mm equivalent diameter hole), R2 (catastrophic rupture – release of the entire inventory in 600 s), R3 (catastrophic rupture – instantaneous release of the entire inventory), R4 (pipe leak – continuous release from a hole having 10 % of pipe diameter), R5 (pipe rupture – continuous release from the full-bore pipe) (Uijt de Haag and Ale, 2005). For each accident scenario (i.e., fire, explosion, toxic cloud) possibly originating from LOCs of units, a damage distance (DD), defined as the distance at which the consequence of the considered scenario equals a given threshold value, is computed in Step 3 using conventional consequence analysis models (e.g., see Van Den Bosh and Weterings, 2005). Threshold values are expressed with reference to human targets and gathered from Tugnoli et al. (2007). In Step 4, credit factors (C_fs), quantifying the proneness of equipment items to give rise to the defined LOCs, are assessed considering leak frequency data reported in the literature (Uijt de Haag and Ale, 2005) for conventional process equipment. Based on DDs and C_fs evaluated in the previous steps, inherent safety key performance indicators (IS-KPIs) are calculated in Step 5 for each reference PS, according to the following set of equations:

$$UPI_i = \pi \max_j \left(\max_k DD_{i,j,k}^2 \right) \tag{1}$$

$$UHI_i = \pi \sum_j C_{fi,j} \cdot \max_k DD_{i,j,k}^2 \qquad (2)$$

$$UPI_{max} = \max_i UPI_i \qquad (3)$$

$$UHI_{max} = \max_i UHI_i \qquad (4)$$

$$PI = \sum_i UPI_i \qquad (5)$$

$$HI = \sum_i UHI_i \qquad (6)$$

where $DD_{i,j,k}$ and $C_{fi,j}$ are respectively the damage distance associated with the *k*-th accident scenario possibly arising from the *j*-th LOC of the *i*-th unit and the credit factor related to the *j*-th LOC of the *i*-th unit. *UPI* and *UHI* represent the unit potential hazard index and unit inherent hazard index respectively. On the other hand, the overall potential hazard index and overall inherent hazard index, respectively *PI* and *HI*, are meant to describe the safety performance of the reference PS as a whole.

Ultimately, the inherent safety footprint (IS-F) metric is introduced to rank the safety performance of the alternative reference ship PSs considered (Step 6). In this context, representative IS-KPIs of reference PSs, i.e., expressed by Equations (3)-(6), are subject to internal normalisation with respect to their maximum figures in the analysis and reported on a radar plot. IS-F can then be computed graphically as the ratio of the area of the quadrilateral associated with the given PS and the surface area of the overall radar chart.

3. Case study

The reference ship PSs specified in the present study are reported in Table 1. An LNG-based PS was defined as the benchmark for the comparative inherent safety assessment. The onboard implementation of PSs was considered for a reference Hyperion-class cruise vessel (The Maritime Executive, 2016). Alternative PSs were designed based on 36 MW of nominal power capacity and 10 days of ship fuel autonomy as requirements (Iannaccone et al., 2020). Liquid hydrogen (LH_2), compressed gaseous hydrogen (CGH_2), and cryo-compressed hydrogen ($CcLH_2$) were analysed at this scope. It is worth noting that different alternatives can be considered for the cryo-compressed hydrogen case. Indeed, storing hydrogen at a temperature included within the range of 120 K – 180 K and pressure in the proximity of 350 bar is typically referred to as cryo-compressed gas, whereas lowering the temperature at about 30 K (i.e., the boiling temperature corresponding to the operative pressure) will result in a so-called cryo-compressed liquid system (Ahluwalia et al., 2010). The latter shows higher potential because of the increased density due to the liquid form (Durbin and Malardier-Jugroot, 2013) and thus will be investigated in this work. Based on the solutions available in the current literature, storage temperature, pressure, and typical tank dimensions were selected for each scheme (Zanobetti et al., 2023a). Regardless of the selected storage strategy, the use of proton exchange membrane fuel cells was assumed for the hydrogen conversion step, following the recommendations provided in the literature (van Biert et al., 2016). Simplified reference schemes were then developed, including storage tanks as well as process equipment (e.g., heat exchangers, compressors, separators) required to condition the fuel for final utilisation. For the sake of conciseness, the obtained process flowsheets together with additional information on the analysed PSs can be found elsewhere (Zanobetti et al., 2023a).

Table 1: Reference power systems considered in the analysis

		Storage			
Power system	Fuel	Temperature (°C)	Pressure (bar)	Physical state	Utilisation technology
LH_2 - PEMFC	Hydrogen	-252.8	1.0	Liquid	PEMFC
CGH_2 - PEMFC	Hydrogen	20.0	350.0	Gas	PEMFC
$CcLH_2$ - PEMFC	Hydrogen	-252.8	350.0	Liquid	PEMFC
LNG - LBSI	Liquefied natural gas	-133.2	6.0	Liquid	LBSI

4. Results and discussion

Based on the described methodology, the safety performances of the investigated solutions were quantified and expressed in terms of the PI and HI indices reported in Figure 2.

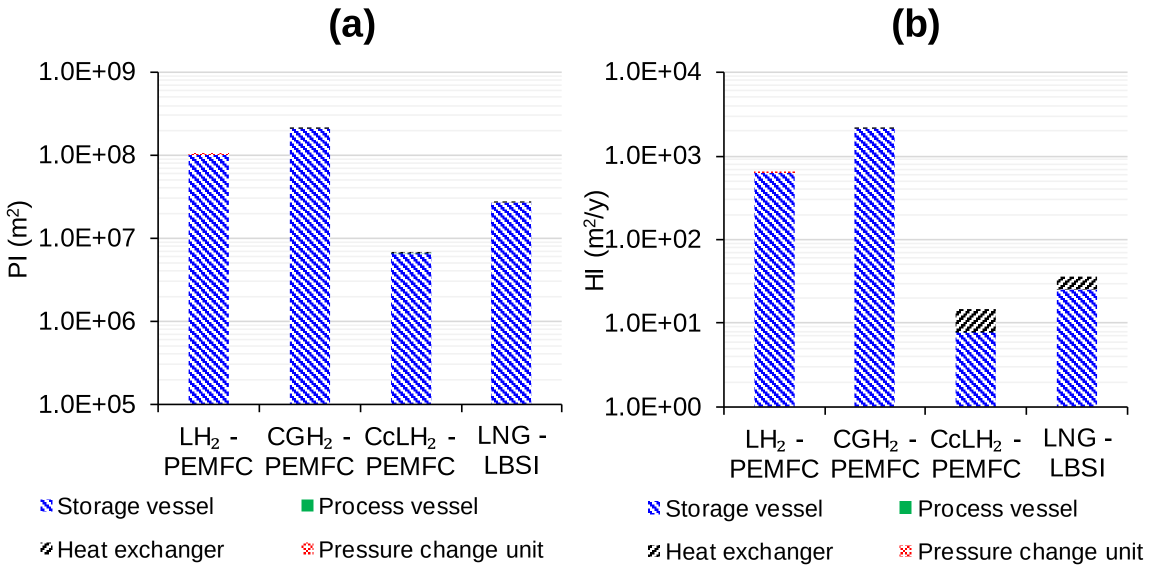

Figure 2: Overall IS-KPIs computed for the reference ship PSs: (a) PI values; (b) HI values

According to both indices, CGH_2 – PEMFC presents the worst inherent safety performance. This can be attributed to the significant severity and credibility of gaseous hydrogen releases from the high number of storage tanks installed onboard. Conversely, the adoption of PSs based on liquid hydrogen, either cryogenic or cryo-compressed, resulted in greatly reducing the overall onboard hazard level. This is particularly relevant for the case of $CcLH_2$ – PEMFC, where PI and HI are respectively almost 6/25 and 2/5 of the values associated with LNG – LBSI. This reduction can be attributed to the larger energy density, resulting in a reduced storage requirement as well as lower credibility of an accidental release due to the construction characteristics of the analysed vessels.

Under the posed hypotheses, the most relevant consequences were generated by vapour cloud explosions for all the reference PSs considered. Hence, the effects of scenarios related to the presence of extremely low temperatures (e.g., frostnip and frostbite) can be considered negligible on the risk figure resulting from this analysis, regardless of the investigated reference scheme.

Focusing on the hazard contributions of single equipment items, storage vessels resulted in the most safety-critical units, accounting for almost the whole values of PI and HI indices for all the reference PSs examined. Remarkably, if focusing on PI, almost negligible contributions can be observed for process vessels, heat exchangers, and pressure change units. Hence, the robustness and validity of the presented results can be extended also in the case of minor modifications within the proposed reference schemes. Conversely, when accounting for the credibility of loss of containment (HI index, Figure 2b), pressure change units (e.g., pumps and compressors) present a slightly increased inherent hazard contribution, due to their higher proneness to failures.

Figure 3 illustrates the calculation of the IS-F for the reference PSs considered in the analysis.

As can be seen from the radar plot, LH_2 – PEMFC and CGH_2 – PEMFC emerge as the worst-performing PSs, given the significantly wide surface areas associated with their inherent safety profile curves. Specifically, the safety performance of LH_2 – PEMFC appears significantly depleted when considering the hazard level of single units. Conversely, CGH_2 – PEMFC turns out to be the least convenient option when summing up unit-based contributions in the overall IS-KPIs.

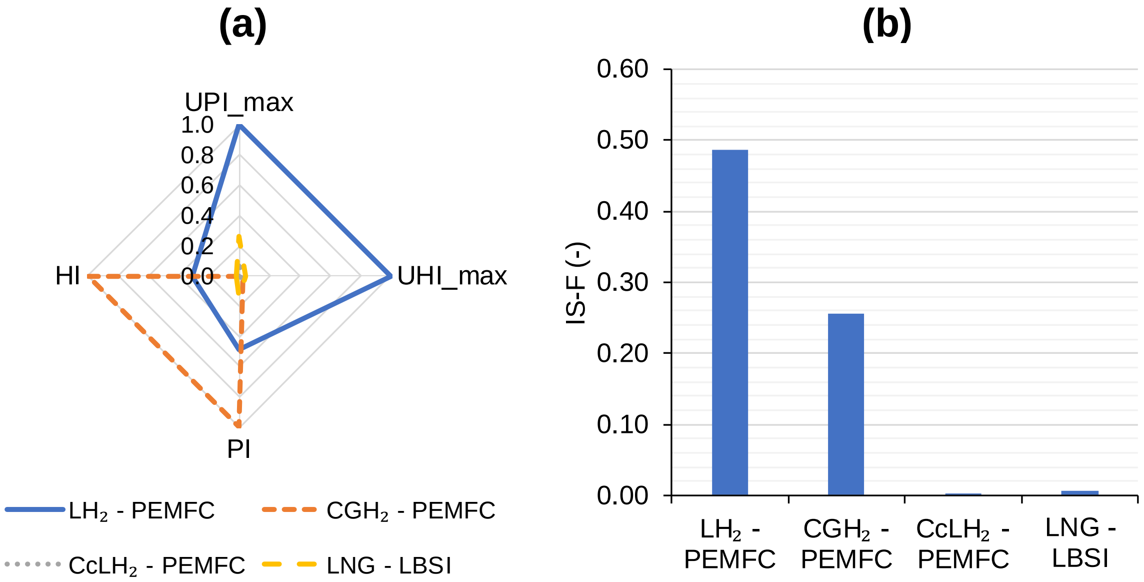

Figure 3: Calculation of IS-F for the reference ship PSs: (a) input radar plot of normalised IS-KPIs; (b) IS-F ranking

Globally, the integrated evaluation of unit- and overall system-based IS-KPIs in the context of the proposed IS-F approach (Figure 3b) highlights that CGH_2 – PEMFC tends to outperform LH_2 – PEMFC, with an IS-F almost 2 times lower. According to the pattern of IS-F values in Figure 3b, only hydrogen-based concepts employing advanced cryo-compressed liquid technologies may result in being inherently safer than the baseline LNG-based power system.

5. Conclusions

A newly developed approach to the comparative inherent safety assessment of alternative hydrogen-based PSs was presented. This consists of evaluating representative IS-KPIs and using them as input to generate an IS-F-based ranking of reference PSs. A long-range cruise vessel was considered as a case study for the implementation of alternative PSs. Reference hydrogen-fuelled PSs were designed considering typical storage modes and utilisation systems recommended in the literature. Generally, storage vessels resulted in the equipment category with the lowest safety score, regardless of the inherent safety metric considered. This highlights that the onboard inherent hazard level of the ship power system could be greatly reduced if proper inherently safer design measures targeting storage systems are implemented. The calculation of IS-KPIs showed that the alternative based on cryogenic liquid hydrogen results penalised by the poor safety score of its constituting units, while the significant number of storage tanks installed onboard render the compressed gaseous hydrogen-based system the overall inherently least safe option. When integrating unit and overall indices in a broader IS-F perspective, the replacement of LNG engines with either cryogenic liquid hydrogen-based or compressed gaseous hydrogen-based systems increased the onboard inherent hazard level. Conversely, solutions with hydrogen stored as cryo-compressed liquid could lead to enhancements in the inherent safety performance of the ship power system. The analysis shed light on the potential of cryo-compressed hydrogen-based systems, currently having the lowest technological readiness level among the alternative concepts considered, as a possible long-term inherently safer solution for hydrogen utilisation as a marine fuel. Ultimately, the step-by-step procedure developed could be extended to support inherent safety-driven decision-making and design concerning other emerging cleaner fuel-based concepts (e.g., ammonia-based, methanol-based, etc.).

Nomenclature

PS – power system
LNG – liquefied natural gas
LH_2 – liquid hydrogen
CGH_2 – compressed gaseous hydrogen
$CcLH_2$ – cryo-compressed liquid hydrogen

LBSI – lean burn spark ignition
PEMFC – proton exchange membrane fuel cell
SOFC – solid oxide fuel cell
LOC – loss of containment

DD – damage distance
C_f – credit factor
IS-KPI – inherent safety key performance indicator
IS-F – inherent safety footprint

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