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Benchmarking of Novel Insulation Concepts for Liquid Hydrogen Storage Tanks

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Hydrogen is a promising energy carrier for achieving carbon-neutral solutions across multiple sectors. Liquid hydrogen (LH_2) offers a high volumetric energy density for storage and transport; however, the scalability of current large-scale LH_2 tanks is limited by complex fabrication processes and demanding operational requirements. To address these challenges, the European NICOLHy project investigates novel insulation architectures based on Vacuum Insulation Panels (VIPs) to enable the scale-up of state of the art LH_2 storage systems for large-scale applications. This work presents a comparative benchmarking methodology based on a set of Key Performance Indicators (KPIs) to address safety, performance and sustainability aspects supporting the early-stage assessment of innovative LH_2 storage insulation concepts. The approach builds upon a multi-criteria screening framework originally developed by NASA for LH_2-fueled aircraft, which is adapted to the project objectives and boundary conditions. The applicability of the methodology is demonstrated through a preliminary, safety-oriented qualitative benchmarking of selected insulation concepts, including a state of the art configuration and novel VIPs-based solutions. Although limited by the current availability of quantitative data, the results illustrate the ability of the proposed framework to highlight strengths, limitations and safety implications of early-stage design concepts. The methodology is conceived as an iterative decision-support tool, contributing to the development of safe and scalable LH_2 storage systems for future hydrogen supply chains.

Keywords: Liquid hydrogen, hydrogen safety, cryogenic storage tank, vacuum insulation panel, benchmarking, key performance indicator.

1. Introduction

The European Green Deal strategy was launched in 2019 to initiate the transition toward a sustainable and climate-neutral economy by 2050. Approximately $75\,\%$ of total greenhouse gas emissions are attributable to energy production, highlighting the urgent need to make energy generation more sustainable. In this context, the European Union is implementing supporting measures to foster the development of a hydrogen-based economy, recognizing hydrogen as a versatile and potentially low-carbon energy carrier (Council (2019)). Liquid hydrogen (LH_2) represents an attractive option for hydrogen storage due to its higher volumetric energy density ($8.54\,\mathrm{MJ/L}$ (Usman (2022))) compared to compressed gaseous hydrogen ($5.6\,\mathrm{MJ/L}$ at 700 bar (Møller et al. (2017))), thereby reducing the space required for storage infrastructures. As the hydrogen economy expands, the demand for efficient and scalable LH_2 containment systems is expected to grow substantially. The current state of the art for stationary LH_2 storage relies on double-walled vacuum-insulated spherical vessels, with maximum storage capacities of approximately $4{,}700\,\mathrm{m}^3$ (Ratnakar et al. (2021)). However, the scalability of these tank designs is limited by several factors, including long production times, limited failure tolerance and high structural complexity, which significantly reduce the payload efficiency (Campari et al. (2025)). In this contest, the European NICOLHy project investigates novel insulation architectures based on Vacuum Insulation Panels (VIPs) to enable stationary storage capacities of LH_2 up to $200{,}000\,\mathrm{m}^3$, while overcoming the limitations of conventional insulation solutions and meeting safety, performance and cost requirements (Clean Hydrogen JU (2024)). Given the early stage of design of these concepts and the limited availability of consolidated quantitative data, structured decision-support tools are required to guide concept development and identify critical design weaknesses.

This work presents a methodology for the comparative assessment of novel LH_2 insulation concepts, building upon a NASA multi-criteria screening approach originally developed for the design of LH_2-fueled aircraft (Brewer et al. (1978)). The methodology is adapted to the specific objectives and boundary conditions of large-scale stationary LH_2 storage. A preliminary application of the method is demonstrated through the qualitative comparison of selected insulation concepts proposed by the NICOLHy partners, focusing on safety-related Key Performance Indicators (KPIs). In this context, the technological background and reference framework are introduced in Sec. 2, while Sec. 3 presents the adapted benchmarking methodology and its application and Sec. 4 discusses the resulting safety-oriented comparison.

2. State of the Art

The following section reviews the state of the art relevant to scaling up stationary LH_2 storage systems to large capacities. Sec. 2.1 discusses existing LH_2 tanks and their scale-up limitations, Sec. 2.2 introduces the NICOLHy research objectives and Sec. 2.3 presents the NASA benchmarking methodology used as reference.

2.1. *Limitations of large-scale LH_2 storage tanks*

The state of the art in large-scale LH_2 stationary tanks relies on spherical, double-walled, vacuum-insulated vessels operating at pressures slightly above atmospheric conditions and capable of storing a few thousand cubic meters of LH_2. For these capacity ranges, the spherical tank shape is preferred over the cylindrical one. Firstly, because of its optimal surface-to-volume ratio, which ensures minimal heat ingress from the environment and, consequently, lower boil-off gas (BOG) generation. Secondly, the stress distribution along the structure is uniform, allowing thinner structural walls compared to cylindrical vessels operating at similar pressures (Wang and Mérida (2024),Campari et al. (2024)). Long-term storage at $20\,\mathrm{K}$ is enabled by micro-porous insulating materials (e.g., perlite, hollow glass microspheres (HGMs)) or multi-layer insulation (MLI), which operate under high-vacuum conditions, thus further reducing convective and conductive heat transfer (Campari et al. (2024)). Currently, the largest operational LH_2 storage tanks that show these features are the $2{,}500\,\mathrm{m}^3$ tank at the HyTouch facility in Japan, operated by Kawasaki Heavy Industries and the $3{,}200\,\mathrm{m}^3$ storage tank at the NASA Kennedy Space Center in Florida, which have supported space launch activities since the Apollo program (Ratnakar et al. (2021),Kim et al. (2024)). Additionally, in 2022 NASA completed the construction of the $4{,}700\,\mathrm{m}^3$ LH_2 storage tank to support launch vehicle fueling for the Artemis program (Swanger (2022)).

The establishment of a future hydrogen economy increases the demand for efficient and scalable LH_2 storage systems. However, significant challenges arise when considering the scaling-up of existing LH_2 tanks to storage volumes of hundreds of thousands of cubic meters, comparable to those of operational liquefied natural gas (LNG) storage systems. LNG is stored at approximately $110\,\mathrm{K}$ in containers that reach capacities up to $230{,}000\,\mathrm{m}^3$ and rely on cylindrical single-wall vessel geometries and an insulation system operating at ambient pressure (Ratnakar et al. (2021)). In this context, scaling spherical LH_2 tanks to such volumes becomes increasingly impractical. As the radius of the vessel increases, the relative benefit of the surface-to-volume ratio diminishes and structural complexity, manufacturing costs, construction time and the mass of support systems increase substantially. Furthermore, maintaining high-quality vacuum conditions on large annular volumes becomes demanding in terms of evacuation time, cost and long-term reliability. However, LH_2 is characterized by a lower boiling temperature and a lower latent heat of vaporization compared to LNG, which implies the need for insulation systems with significantly higher thermal performance. The introduction of non-vacuum insulation systems for LH_2 storage also raises safety concerns, as air in contact with tank surfaces can reach temperatures below the boiling points of its constituents (oxygen at $90\,\mathrm{K}$ and nitrogen at $77\,\mathrm{K}$), leading to condensation and freezing phenomena. This may degrade the insulation performance and promote the formation of oxygen-enriched zones, which can lead to hazardous failure scenarios (Campari et al. (2024),Ratnakar et al. (2021)).

Since these limitations make the scale-up of conventional LH_2 tanks impractical, they reveal a clear technological gap between current storage solutions and the capacities required for future hydrogen supply chains, motivating the investigation of alternative storage and insulation concepts.

2.2. *The NICOLHy project*

The NICOLHy project (Grant Agreement No. 101137629) is funded by the European Union to investigate novel insulation systems to enable the safe and energy-efficient storage of large quantities of LH_2 (Clean Hydrogen JU (2024)). The main objective of the project is to reach onshore LH_2 storage capacities exceeding $200{,}000\,\mathrm{m}^3$ and maritime application capacities up to $40{,}000\,\mathrm{m}^3$, while limiting the BOG generation to $0{,}1\,\mathrm{mass}-\%/\mathrm{day}$ and maintaining storage costs below $20\,/\mathrm{kg}$. To overcome the limitations associated with scaling up state of the art large LH_2 storage tank designs, the project investigates for the first time the use of VIPs as the core element of novel insulation concepts (Campari et al. (2025)). A VIP is a flat insulating structure consisting of an evacuated porous core material enclosed within a gas-tight envelope, which preserves the vacuum and significantly limits conductive, convective and radiative heat transfer. In recent decades, VIPs have been widely adopted in the building sector due to their high insulation performance at reduced thickness compared to conventional insulation systems (Alam et al. (2011)). These characteristics make VIPs particularly attractive as potential alternatives to commonly used cryogenic insulation materials for LH_2 storage tanks. Beyond improved thermal performance and potentially reduced production costs, the use of VIP-based insulation concepts offers additional advantages. The system is inherently scalable and modular, facilitating application to very large storage volumes. Moreover, modular insulation layouts may simplify inspection and maintenance procedures, thereby increasing failure tolerance. The possibility of parallel manufacturing and installation of insulation modules may also contribute to a reduction in overall tank construction time (Campari et al. (2025)).

To achieve the project targets, the NICOLHy consortium adopts a holistic approach, simultaneously addressing performance, safety, cost and sustainability aspects. Several storage and insulation concepts have been proposed and a benchmarking-based methodology is applied to systematically compare them and identify solutions that best meet the expected requirements.

2.3. *NASA benchmarking approach*

A previous study developed by NASA has been adopted as a reference framework for the present analysis. In 1978, NASA proposed a structured methodology to support the selection and preliminary assessment of LH_2 fuel containment systems for transport aircraft. The objective of the study was to identify configurations capable of meeting safety, performance and cost requirements, progressively narrowing down design options toward a final realization stage (Brewer et al. (1978)).

A multi-criteria benchmarking approach was applied, articulated into three sequential phases characterized by increasing levels of analysis detail: (i) screening of proposed concepts, (ii) evaluation of preferred candidates and (iii) selection of the final configuration. This section describes only the first phase of the methodology, as it is the one adopted in this study. In the screening phase, fifteen insulation candidates were evaluated to identify the most promising solutions for further investigation in the subsequent evaluation stage. Each concept was presented by a bidimensional sketch, specifying the insulation type, operational conditions and constituent materials. For consistency, all insulation systems were assumed to be applied to the same reference containment tank architecture. This assumption allowed the comparison to focus on insulation-related aspects. The screening analysis was centered on three main categories: safety, performance and producibility. For each category, several criteria were defined to capture different aspects of the design. Specifically, the safety ranking criteria include malfunction behavior, leak detection capability, flammability and toxicity and inspectability. Some of these criteria included sub-criteria to capture potential safety issues associated with different design solutions. Moreover, a numerical weighting factor was assigned to each indicator to reflect its relative importance: a score equal to four denoted the highest relevance and a score of one indicated the lowest impact on aircraft and passenger safety (see Table 1).

At this screening stage, a qualitative evaluation was employed and a ranking scale was adopted to allow a first-order comparison between the proposed configurations. The resulting scores were normalized on a 100-score scale to allow comparison between concepts. Additionally, similar approaches were applied to evaluate performance and productivity criteria. Finally, to facilitate the comparison between concepts, one configuration was selected as the baseline and the values of the three categories for each concept were normalized with respect to it. In this way, the screening procedure allowed the identification of a reduced set of four concepts to be considered in the subsequent evaluation phase.

3. Methodology

This section describes the benchmarking framework adopted in this study. Sec. 3.1 presents the methodology and workflow used to adapt the NASA multi-criteria screening approach to the project objectives. Then, Sec. 3.2 illustrates a methodology application to a representative case study, focusing on selected insulation concepts and safety-related KPIs.

Table 1. Safety ranking criteria for LH_2 aircraft (adapted from Brewer et al. (1978))

Criteria	Ranking weight
Malfunction	
Barriers	
• *Permeability and leakage*	4
• ΔP *and flow direction*	2
• *Effect of thermal cycles*	3
• *Resistance to accidental penetration*	4
Active systems	3
Leak detection and control	
Time	1
Sensitivity	1
Safe removal in service	3
Safe removal for tank inspection	1
Flammability and toxicity	2
Inspectability	
Tank	1
Barrier	1

3.1. *NICOLHy benchmarking approach*

The benchmarking method is based on the NASA methodology described in Sect. 2.3 and is applied to novel insulation concepts. A total insulation thickness of one meter and a cylindrical tank geometry with fixed height and diameter are assumed for all cases, allowing the analysis to focus exclusively on differences in the insulation system architectures.

Consequently, a set of safety-related KPIs has been identified to evaluate and compare the proposed concepts. The criteria adopted in this framework differ from those used in the original NASA study, as they are tailored to the specific objectives of the NICOLHy project and to safety issues relevant to large-scale stationary LH_2 storage applications, such as air condensation avoidance.

Subsequently, the KPIs were classified as qualitative or quantitative. Qualitative KPIs are evaluated based on expert judgment and assigned discrete normalized scores on a 100-point scale (0, 25, 50, 75, 100), in line with the NASA screening approach. On the other hand, quantitative KPIs are evaluated using numerical values derived from dedicated analyses performed by the project partners. Depending on the nature of the KPI, normalization is performed either by maximizing or minimizing the associated value, as in Eqs. (1) and (2).

$$S_{i_{\max}} = 100\,\frac{x_i - \min(x)}{\max(x) - \min(x)} \qquad (1)$$

$$S_{i_{\min}} = 100\,\frac{\max(x) - x_i}{\max(x) - \min(x)} \qquad (2)$$

Where x_i denotes the value of the considered KPI for concept i,while $\max(x)$ and $\min(x)$ represent the maximum and minimum values of that KPI among all analyzed concepts, respectively. Eq. (1) is applied to KPIs for which higher values correspond to better performance, whereas Eq. (2) is used for KPIs to be minimized.

Following the NASA screening methodology, each KPI is assigned a weighting factor ranging from 1 to 4 to reflect its relative importance. In this work, the weighting factors also account for the evaluation confidence level, with quantitative KPIs considered more reliable than qualitative ones. Consequently, the final benchmarking score for each concept is computed by summing the weighted normalized KPIs and normalizing the result on a $0 - 100$ scale, as expressed in Eq. (3).

$$S_{\text{concept}} = \frac{\sum_{i=1}^{N} S_i\, w_i}{\sum_{i=1}^{N} w_i} \qquad (3)$$

where S_i is the normalized score of the i-th KPI and w_i is the corresponding weighting factor.

A Python-based algorithm is used to implement the benchmarking workflow. The algorithm takes in input qualitative and quantitative KPI values and their weighting factors, applies the normalization procedures, and computes the results, generating comparative charts to support the analysis. This multi-level normalization approach enables intuitive KPI-level comparisons through the initial normalization and a consistent overall concept ranking through Eq. (3).

Lastly, it is essential to stress that, while the original NASA screening procedure aims to exclude some configurations to select preferred solutions for subsequent development stages, the benchmarking methodology employed in this work is conceived as an iterative process. Indeed, each analysis step serves to identify the weaknesses of the initial conceptual designs, thus supporting further improvements to progressively refine the level of design complexity in subsequent phases (e.g., investigating alternative materials or introducing different support and hanging systems of VIPs). This iterative approach enables the exploration of multiple design solutions, contributing to increased system resilience and overall optimization.

3.2. *Case study definition*

The benchmarking procedure presented in this study is applied to three insulation architectures. Concept 0 (C0), shown in Figure 1(a), represents the state of the art insulation system for large-scale LH_2 storage tanks and serves as the baseline for the comparative assessment of the other configurations. The insulation consists of evacuated HGMs enclosed within a double-wall structure. Concepts 1 and 2 (C1 and C2) are novel insulation architectures, depicted in Figure 1(b) and Figure 1(c), respectively. Both are conceived as double-layer insulation systems, in which a gas-tight membrane separates an inner and an outer chamber. The two concepts share the same insulation layout in the outer section, composed of staggered and overlapped VIP layers. In addition, the outer chamber is swept with nitrogen at a slight overpressure relative to ambient conditions, to prevent air ingress in the event of accidental leakages. Conversely, the inner chamber differs between the two configurations. In C1, it is filled with evacuated HGMs, whereas in C2 is formed by staggered multilayers of VIPs swept by cold helium at a slight overpressure relative to the nitrogen flow in the outer chamber, again to prevent air ingress.

Within this framework, the safety-related KPIs considered in the benchmarking analysis are defined as follows:

- Fire resistance (FR): the ability of the insulation system to withstand high temperatures

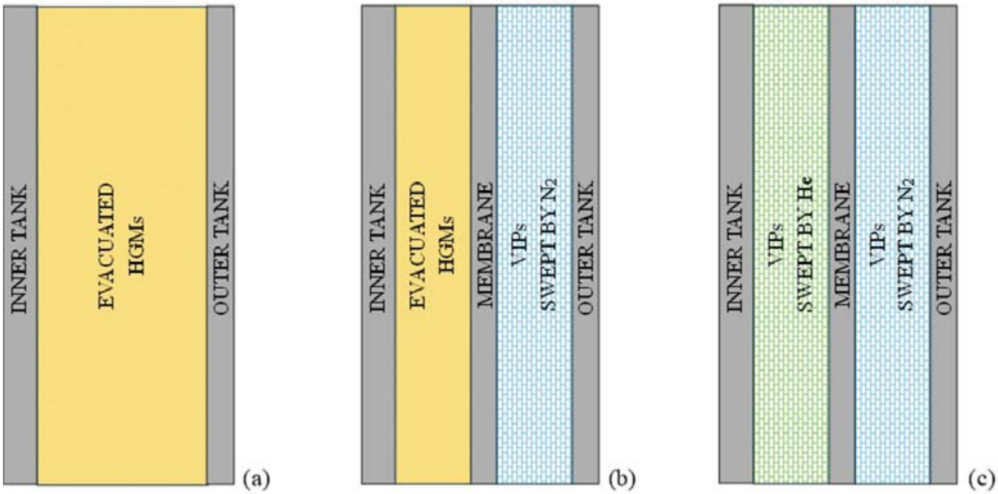

Fig. 1. Schematic cross-sectional views of the insulation concepts: (a) C0, (b) C1 and (c) C2

or flame exposure without loss of load-bearing capability, structural integrity or thermal insulation performance. Considerations on the potential formation of toxic gases during fire scenarios are also included. This KPI is assigned a weighting factor equal to 2, consistent with the relative importance attributed to the same criteria in the NASA screening methodology (Table 1).

- Air condensation avoidance (ACA): as introduced in Sec. 2.1, the formation of oxygen-enriched environments increases the risk of fire and explosion in the event of accidental LH_2 release. Additionally, condensation and freezing of air degrade the insulation's thermal performance, leading to increased boil-off rates. For this reason, ACA is assigned the highest weighting factor (4), as it represents a key safety requirement for large-scale stationary LH_2 storage systems.

Due to the preliminary design stage of the concepts and the current absence of consolidated numerical data, the evaluation in this study follows a qualitative approach. The benchmarking workflow is implemented using a Python-based algorithm, as described in Sec. 3.1, to process the scores and compute the final comparison metrics.

In addition to the benchmarking analysis, a Failure Modes and Effects Analysis (FMEA) is conducted within the NICOLHy project framework to compare the state of the art configuration with the novel insulation concepts. Starting from the preliminary design of each concept, the analysis identifies potential failure modes, evaluates their effects, and defines mitigation measures aimed at reducing associated risks (AIAG and VDA (2019)). The outcomes of the FMEA provide specific insights into insulation design aspects and support additional safety-related considerations beyond the benchmarking scores.

4. Results and Discussion

The results of the benchmarking analysis are summarized in Table 2, which reports the qualitative scores assigned to each concept together with the associated KPI weighting factors, and in Figure 2, where a histogram highlights the overall safety scores obtained by the analyzed configurations. Figure 2 shows that C2 achieves the highest overall safety score (100 points), followed by C1 (approximately 60 points) and the state of the art configuration, C0 (25 points). From Table 2 it can be observed that both VIP-based concepts outperform the reference configuration with respect to ACA and FR. For ACA, this result is primarily attributed to the presence of insulation chambers actively swept by inert gases, which significantly reduce the likelihood of air ingress and enable the detection of hydrogen leakages. In contrast, the evacuated insulation system is more sensitive to vacuum degradation, which may lead to air ingress and the formation of oxygen-enriched zones. A similar trend is observed for FR: VIP-based insulation concepts benefit from gas-tight envelopes that can act as additional physical barriers under fire exposure, whereas the conventional insulation system relies on a limited number of protective layers, resulting in lower relative performance for this KPI.

Table 2. Safety-benchmarking results

	Weight	C0	C1	C2
ACA	4	25	50	100
FR	2	25	75	100

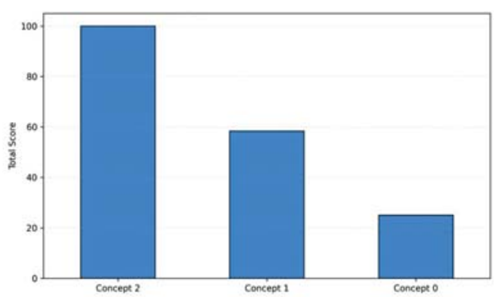

Fig. 2. Safety-benchmarking overall results

In addition to the benchmarking results, FMEA qualitatively assesses potential failure mechanisms associated with the different insulation concepts. Although any FMEA scoring is reported in this work, the analysis supported the high technological maturity of conventional LH_2 insulation systems, whose failure modes are well understood and supported by extensive operational experience. Conversely, the novel VIP-based concepts introduce increased system complexity, mainly due to the integration of active sweeping systems and multiple insulation layers, which may lead to additional failure modes that are not yet fully characterized.

In this context, C2 emerges as the most favorable solution in terms of overall safety performance, driven by its fully VIP-based architecture and enhanced air ingress prevention strategies. At the same time, the increased complexity associated with this configuration emphasizes the need for further investigations aimed at identifying potential failure mechanisms and addressing design-related vulnerabilities in subsequent development phases. Hybrid solutions such as C1, which combine conventional and innovative features, may therefore represent valuable intermediate steps toward improving system resilience while maintaining a manageable level of complexity.

Given the preliminary nature of this study, it is important to stress that the presented results represent an initial application of the proposed benchmarking methodology. In future work, additional aspects such as performance and sustainability, together with their associated KPIs, will be integrated into the benchmarking framework. This extended analysis will allow a more comprehensive comparison of the proposed concepts and may drastically change the final ranking outcomes.

5. Conclusion

This work presented an adapted benchmarking methodology to support the early-stage assessment of insulation concepts for large-scale stationary LH_2 storage. The approach builds on a NASA multi-criteria screening framework and is tailored to the NICOLHy project objectives. A preliminary qualitative application showed the ability of the method to highlight safety-related considerations despite the current lack of consolidated quantitative data. The proposed framework provides a structured and iterative decision-support tool to guide the development and refinement of scalable LH_2 storage systems design.

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