Comparative life cycle assessment of different vacuum insulation panel core materials for cryogenic storage tanks – with a focus on glass bubbles as a novel core material

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***Abstract*— Developing a sustainable hydrogen supply chain is important in facilitating the energy transition towards climate neutrality. Hydrogen in its free form can be stored and transported either as a gas or a liquid. Due to gaseous hydrogen's comparatively low energy density, liquefied hydrogen (LH_2) is often preferred, especially with regard to long-distance transportation and storage in bulk. A notable challenge associated with LH_2 is the inherent requirement to preserve it at a low temperature of -253°C. Consequently, the utilisation of thermally insulated tanks is necessary to minimise LH_2 evaporation. There is a lack of literature on the environmental impacts of insulation materials and concepts for cryogenic storage tank applications in the hydrogen supply chain. Hence, this study investigates a novel concept, namely vacuum insulation panels (VIPs), focusing on their core materials, with a view to assessing their environmental sustainability and circularity. A cradle-to-grave life cycle assessment (LCA) model is employed to investigate six distinct VIP core materials, namely, silica aerogel, rigid polyurethane foam, expanded perlite, glass fibre, fumed silica, and glass bubbles (hollow glass microspheres), with a special focus on the latter. The LCA results show that polyurethane foam and silica aerogel rank low in environmental performance, making them less suitable as primary choice. Expanded perlite is the most environmentally friendly material option, followed by glass fibre, glass bubbles, and fumed silica. Improvements to the environmental impact of glass bubbles can be achieved via the implementation of closed-loop recycling in their life cycle.**

Keywords—Hydrogen, vacuum insulation panels (VIPs), glass bubbles, hollow glass microspheres (HGM), life cycle assessment (LCA), cryogenic storage tanks.

I. INTRODUCTION

The storage of liquid hydrogen (LH_2) in its pure and most volumetric energy dense form at 20 K – particularly relevant to applications with limited space like long-distance transportation via ships – poses considerable challenges [1], [2], requiring custom designed insulation systems. A novel concept for LH_2 storage insulation are vacuum insulation panels (VIPs). They have the potential to enable sustainable large-scale storage of LH_2, being an energy- and cost-efficient and multiple-failure tolerant insulation [3]. A VIP consists of two basic components: the core and the envelope [4]. A novel material being explored for the core of VIPs is glass bubbles [3]. While they have been studied as an insulation material, not much research has been conducted with regards to their life cycle impact assessment and comparison to other insulation materials in terms of environmental impacts.

Therefore, the aim of this paper is to provide a comparative analysis of the environmental sustainability and circularity of different core materials that can be employed in VIPs for LH_2 storage tanks with a focus on glass bubbles.

II. LIFE CYCLE ASSESSMENT

The standardized method of life cycle assessment (LCA) (ISO 14040 and 14044) provides a framework for the quantification of potential environmental impacts of products over their life cycle from raw material extraction, production, use, to end-of-life (EoL) management. To conduct an LCA, ISO 14040 defines the four iterative phases of goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation [5].

A. Goal and Scope definition

The goal is to identify the most environmentally sustainable core material for VIPs used for LH_2 storage tanks via an attributional LCA, to support the eco-design of such tanks. Different VIP core materials, namely, glass bubbles, expanded perlite, glass fibre, rigid polyurethane (PUR) foam, silica aerogel, and fumed silica, are compared. The functional unit is defined as the amount in kg of VIP core material required to provide a thermal resistance of 1 m^2W/K for an area of 1 m^2 under cryogenic vacuum conditions (cold boundary temperature: 78 K, warm boundary temperature: 293 K, vacuum pressure: 0.0133 Pa)[1] and is expressed as:

$$FU[kg] = R[\frac{m^2K}{W}] \cdot \lambda[\frac{W}{mK}] \cdot \rho[\frac{kg}{m^3}] \cdot A[m^2] \qquad (1)$$

Where: *FU*: functional unit, *R*: thermal resistance of the core material, λ: thermal conductivity of the core material, ρ: density of the core material, *A*: area that is covered by the core material. The study spans the entire life cycle from cradle-to-grave, excluding the manufacturing and use of the VIP, and only accounting for the core materials' EoL treatment.

B. Life cycle inventory analysis

This subsection describes the modelling of the life cycle inventory. The LCI data are collected from the ecoinvent database (v.3.11, "cut-off") [6] and existing literature.

1) Raw material and manufacturing stages

The raw material and manufacturing stages for expanded perlite, glass fibre, and PUR foam are modelled directly using the ecoinvent database [6]. Comprehensive data collection activities are carried out to model the production of glass bubbles, silica aerogel, and fumed silica.

2) End-of-life stage

Modelling the LCI of the EoL stage is performed using ecoinvent's cut-off system approach. Using this approach, the generator of waste is responsible for its impact, and recycled products only bear the impact of the recycling process, so they are available burden-free to the next user (cut-off) [7].

C. Life cycle impact assessment

The LCIA is conducted according to the environmental footprint v. 3.1 method's 16 midpoint impact categories [8]. The Activity Browser (v. 2.11.1) [9] software is used to conduct the LCIA.

D. Sensitivity analysis

The sensitivity analysis focuses on glass bubbles as these are the main subject of the study. The scenarios (Sc.) studied are: changing the heat source from natural gas to: wood-chips based renewable heat (Sc.1.1) and hard coal-based heat (Sc.1.2); changing the electricity grid mix to: onshore wind, 1-3 MW turbine (Sc.2.1) and hard coal-based electricity (Sc.2.2); and closed-loop recycling of glass for glass bubbles: 27.5% of recycled material[2] used in glass bubble production (Sc.3).

III. RESULTS AND DISCUSSION

The normalized environmental impacts of the assessed core materials are shown in Fig. 1. Among them, silica aerogel exhibits the highest impacts across 13 categories, followed by PUR foam with the highest score in the remaining 3 categories. Each of the 16 impact categories are given similar importance, which is why the results indicate that silica aerogel, followed by PUR foam, are the least environmentally sustainable materials. The findings indicate, that the most environmentally friendly material is expanded perlite, which outperforms the remaining materials in 11 impact categories. It is followed by glass bubbles, which demonstrated better performance in 3 categories, and glass fibre, which excelled in 2 categories. Apart from silica aerogel and PUR foam, fumed silica only exceeds certain materials in specific categories.

Silica aerogel and PUR foam are excluded from further in-depth analysis due to their comparatively poor environmental performance. It is conducted on the example of the impact categories climate change (Fig. 2), and human toxicity, non-cancer (Fig. 3). The analysis is divided into stages, with each evaluated for its environmental impact. The manufacturing stage poses the main environmental burden both for glass fibre and glass bubbles. For expanded perlite, the material stage is the most significant. In the case of fumed silica, the material stage is more dominant. The EoL stage shows only minor contributions from each material to its overall impacts.

The results of the sensitivity analysis (Fig. 4, Fig. 5) show that switching to renewable electricity based on 100% wind power has the potential to improve the overall environmental performance, which is not necessarily the case for the considered renewable heat source. The implementation of closed-loop recycling of glass bubbles has the potential to improve the overall environmental performance.

[1] Due to limited data availability at LH_2 temperatures, the temperature conditions of liquid nitrogen are adopted.

[2] This equates to the average of cullet that can be fed into the manufacture of glass tubes (15-40% may be fed into the furnace) [10].

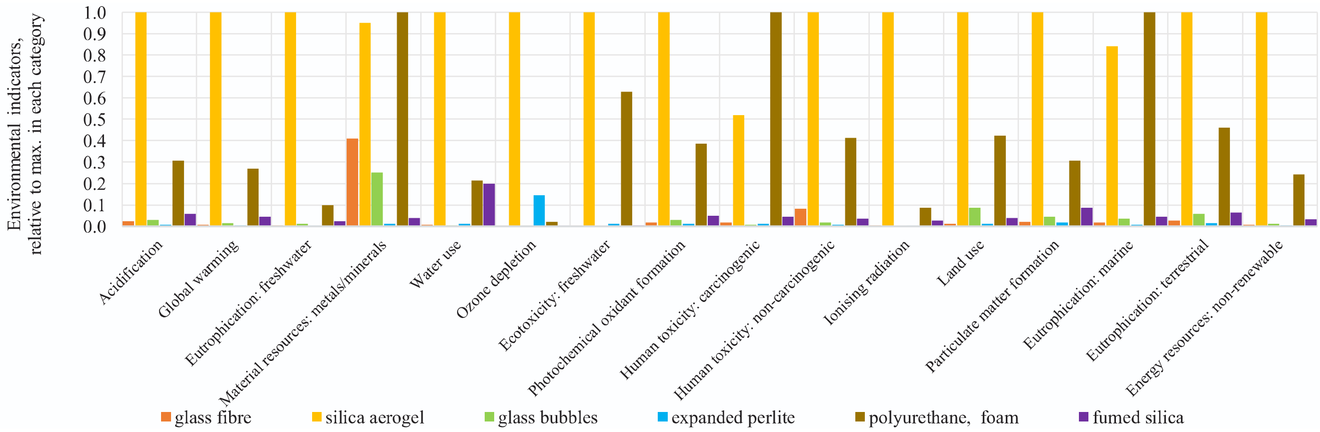

Fig. 1. LCIA results from cradle-to-grave as indicators relative to the maximum in each category, the maximum is set to 1 with the other values scaled accordingly

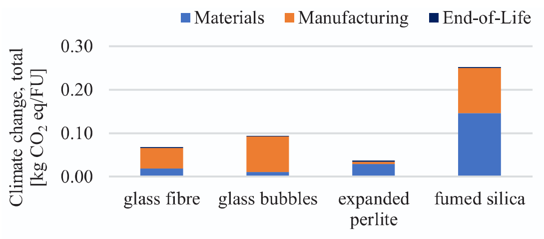

Fig. 2. Global warming potential of selected core materials in kg CO_2 equivalents (kg CO_2 eq) per functional unit

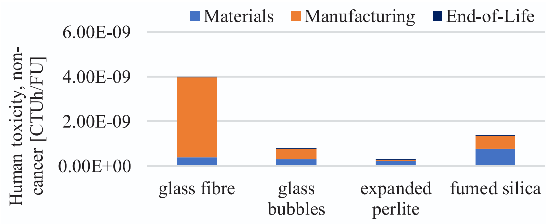

Fig. 3. Human toxicity, non-cancer impact of selected core materials in comparative toxic unit for humans (CTUh) per functional unit

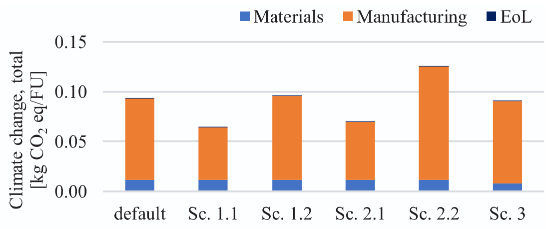

Fig. 4. Sensitivity analysis results of Sc. 1.1 – Sc. 3 of global warming potential in kg CO_2 eq. per functional unit

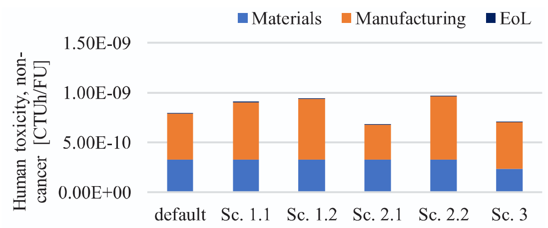

Fig. 5. Sensitivity analysis results of Sc. 1.1 – Sc. 3 of human toxicity, non-cancer impact in CTUh per functional unit

IV. CONCLUSION

This paper investigated the environmental sustainability of six different core materials for vacuum insulation panels used for insulating cryogenic liquid hydrogen storage tanks. A comparative cradle-to-grave life cycle assessment was performed to identify the least and most environmentally sustainable materials. The materials were assessed across their entire life cycle – from raw material extraction and manufacturing to end-of-life treatment and recyclability. Out of the six materials, silica aerogel and rigid polyurethane foam were found to exhibit the highest environmental impacts. Consequently, only glass bubbles, glass fibre, expanded perlite, and fumed silica were investigated further. Among these, expanded perlite demonstrated superior performance in the majority of impact categories, followed by glass fibre, glass bubbles, and fumed silica. Moreover, the overall environmental performance can be improved by using a fully renewable electricity source and adopting closed-loop recycling. Finally, the environmental performance of core materials is not the only criterion required for the selection of the most appropriate core material. Other requirements, such as thermal and mechanical performance, should also be taken into consideration.

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