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Comparative life cycle assessment of vacuum insulation panel core materials for liquid hydrogen storage tanks – glass bubbles compared to conventional core materials

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ABSTRACT

The environmental performance of insulation materials for liquid hydrogen storage tank application is important to the development of sustainable supply chains. As new materials keep evolving, there is a need to assess their environmental impact. Therefore, this study investigates the environmental sustainability and circularity of cryogenic insulation concepts, namely vacuum insulation panels (VIPs), exclusively focussing on their core materials. Employing a cradle-to-grave life cycle assessment model, the VIP core materials are investigated with a special focus on glass bubbles. Based on the results, the global warming potential of the considered core materials, namely, glass bubbles, silica aerogel, fumed silica, expanded perlite, glass fibre, and polyurethane foam is $9.21*10^{-2}$, 7.00, $2.50*10^{-1}$, $3.63*10^{-2}$, $6.68*10^{-2}$, and 1.88 kg CO_2 eq. per functional unit, respectively. In general, silica aerogel and polyurethane foam are the least environmentally friendly materials, while the most sustainable is expanded perlite, followed by glass fibre, glass bubbles, and fumed silica.

1. Introduction

Green hydrogen is considered a promising energy carrier, especially for the maritime sector. However, the storage of liquid hydrogen (LH_2) in its pure and most volumetric energy dense form at 20 K poses considerable challenges. LH_2 is particularly relevant to applications with limited space like long-distance transportation via ships [1,2]. The challenges associated with the storage of cryogenic liquid hydrogen require custom designed insulation systems. Currently, liquid hydrogen storage tanks are typically double-walled with an evacuated thermal insulation material located in between these walls. The insulation material may be bulk material like perlite, silica particles, or hollow glass microspheres (HGMs/glass bubbles), or based on layers such as multi-layer insulation (MLI) [3]. An insulation concept for LH_2 storage insulation is the use of vacuum insulation panels (VIPs) (see Fig. 1). They have the potential to facilitate the sustainable large-scale storage of LH_2, while being energy- and cost-efficient, safe and multiple-failure tolerant [4]. A schematic of the concept is shown in Fig. 1, demonstrating the potential arrangement of the panels as insulating layer.

A vacuum insulation panel consists of two basic components: the core and the envelope (see Fig. 2). The envelope encases the core and is essential for maintaining vacuum, while the core provides thermal insulation and structural stability to the panel [5]. The edges of the envelope are welded to seal the panel. The weld quality is crucial for the VIP's long-term performance as it helps in maintaining the panel's vacuum [6]. To counteract the ingress of water vapor or gases into the VIP, getters or desiccants are often utilised. Opacifiers are employed to reduce radiative heat transfer [7]. Gas pressures in the range of 0 - 100 Pa are acceptable for VIPs; the lower the pressure, the superior the insulating properties due to reduced gaseous thermal conductivity [8].

Extensive research has been conducted on VIPs in the building industry. Various materials have been explored as potential core materials for VIPs, including polyurethane (PUR) and expanded polystyrene (EPS) foams, fumed/pyrogenic silica, silica aerogels, expanded perlite, glass fibre, and fibre/powder composites [7]. It is important to note that VIP core materials are, in and of themselves, insulation materials. For the

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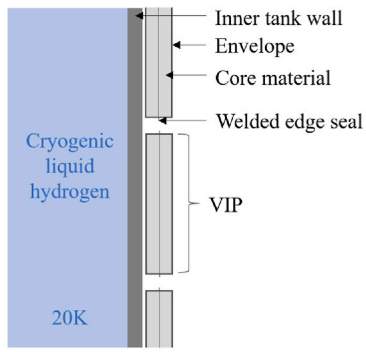

Fig. 1. Schematic of the concept of vacuum insulation panels for insulating a cryogenic liquid tank.

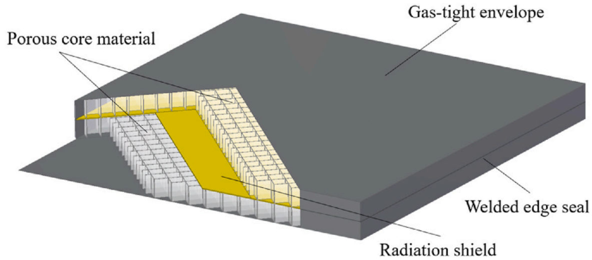

Fig. 2. Schematic of an example of a vacuum insulation panel.

envelope, metal laminates or metalized multilayer polymer laminates are commonly used [5].

In the present study, the insulation materials being explored as VIP core for application in cryogenic storage tanks are glass fibre, expanded perlite, silica aerogel, polyurethane rigid foam, and hollow glass microspheres, with the latter being the material in focus [4]. While glass bubbles 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. That notwithstanding, they have demonstrated superior performance as a substitute for perlites in large-scale spherical, vacuum-jacketed LH_2 tanks. A higher thermal performance resulting in lower boil-off losses and no breakage and compaction due to thermal cycling, was reported for glass bubbles by Baumgartner et al. in Ref. [9]. This suggests strong potential for their usage as a highly effective VIP core material. In a study by Fesmire et al. [10], among others, aerogel beads and perlite powder were compared, showing that the compaction of aerogel beads ceased after a few thermal cycles, whereas perlite compacted further with subsequent cycles. It was reported that aerogel beads demonstrate the best performance for non-evacuated tank applications [10]. To eliminate the issue of compaction of perlite insulation, the micro-fiberglass material (Cryo-Lite®) was developed [11]. Its thermal performance is lower than that of perlite powder in the high-vacuum range, but superior in the ambient pressure range [12]. Due to its low opacity, it is recommended to be applied as a composite with radiation shields [11]. Polyurethane foam has been shown to exhibit superior thermal performance in comparison to glass bubbles and perlite powder under non-vacuum conditions, whereas their thermal conductivity is lower in the high-vacuum range. Therefore, PUR foam is considered suitable for applications where the insulation is exposed to both non-vacuum and vacuum conditions [13].

Swanstrom, Reiss, and Troitsky [14] conducted a study that compared three cryogenic thermal insulation concepts for a liquid nitrogen storage tank from an environmental sustainability perspective. The impacts from manufacturing an evacuated glass fibre insulated storage tank were demonstrated to be the lowest, followed by a tank with a multi-layer insulation and a tank with a polyurethane foam insulation. The insulation performance differed across the concept's compared, with the multi-layer insulation demonstrating the best performance, followed by evacuated glass fibre, and PUR foam. In consideration of the use phase, the environmental impact of the multi-layer insulation outperformed the evacuated glass fibre, followed by the PUR foam [14].

Vacuum insulation panels in the building sector have been comprehensively researched with regards to their environmental sustainability. It has been shown that the core materials are the primary contributors to the overall environmental impact of VIPs [15–17]. However, it cannot be concluded that the same applies for VIPs used in cryogenic applications. The core material is the insulating material in VIPs, hence the present study focuses on their environmental sustainability. A case study involving a VIP with a trilaminate film envelope demonstrated a poor environmental performance of the conventional core material, pyrogenic silica, which was outperformed by expanded polystyrene, glass fibre, and a fibre reinforces silica aerogel in most of the impact categories analysed [15]. A similar observation was made in Ref. [17], where a VIP with a perlite core demonstrated a lower global warming impact than one with a pyrogenic silica core. In comparison to conventional insulation materials, VIPs were shown to exhibit a higher environmental impact. However, they enable efficient insulation in applications where space is limited due to their low thermal conductivity [18].

Due to the novelty of glass bubbles, their environmental impact assessment as VIP core material has not yet been explored. A previous study, investigated glass bubbles as lightweight filler material for polymer composites, showing that their ability to reduce mass and, thus, energy consumption during the use phase of a vehicle can be beneficial in some environmental impact categories. Concurrently, the raw materials involved may be damaging in other categories [19]. Altogether, a comparative analysis of the environmental sustainability of glass bubbles as VIP core material to other core materials has not been conducted at cryogenic or ambient conditions.

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. The life cycle assessment (LCA) approach is employed to assess the various core materials through all life cycle stages from cradle-to-grave. It is important to note that other components of the VIP - envelope, desiccants, and opacifiers - are not regarded. This paper addresses the need to include the environmental sustainability as part of the design of an insulation concept for cryogenic storage tanks. In the conventional design approach parameters such as thermo-mechanical performance and durability are assessed and are already covered in the work by Harwege and Eberwein [20].

2. Life cycle assessment

The standardized method of life cycle assessment (ISO 14040 and 14,044) 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. It is extensively used for environmental product declarations, eco-design of products, and environmental hotspot analysis of specific products, among numerous other applications. To conduct an LCA, ISO 14040 defines the iterative framework as shown in Fig. 3.

The iterative framework begins with defining the goal, which establishes the scope of the study. This entails outlining the study's purpose and application, as well as the expected outcomes. It also involves the specification of the product function being evaluated, along with its functional unit, and the definition of the system boundaries. The functional unit enables the comparison of different products that provide the same function, and is further employed to calculate the reference flow, which is the amount of product required to fulfil the functional unit. The system boundaries delineate the life cycle stages and/or the processes

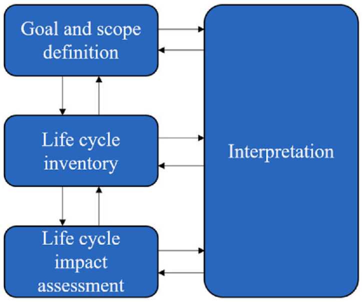

Fig. 3. Framework of life cycle assessment – the four phases based on ISO 14040 [21].

that are included or excluded.

The next phase after the goal and scope definition is the life cycle inventory phase. During this phase, data is collected to model the product system under study. This includes quantifying the input and output flows of the processes involved, which can be elementary flows (i.e. resources or emissions from/to the environment), product flows (i. e. linking the analysed process with other processes), and waste flows. The foreground system comprises the processes specific to the studied product system, whereas the background system contains upstream and downstream processes.

After the life cycle inventory modelling, the environmental impact of the product system life cycle is assessed. This phase involves multiple steps, typically executed with specialised software, to estimate the potential environmental impacts associated with the product system. Sensitivity and uncertainty analyses are optional steps, with the former usually conducted by varying one parameter at a time, and the latter often utilizing uncertainty propagation methods such as Monte Carlo Simulation to account for variability. Finally, the results are analysed in the interpretation phase, where conclusions and recommendations in line with the study's goal are drawn, taking into account limitations such as uncertainties in data collection or underlying assumptions [22].

A Goal and Scope definition

The goal is to evaluate the potential environmental impact of vacuum insulation panel core materials for cryogenic LH_2 storage tank applications via an attributional LCA, to support the eco-design of such tanks. This facilitates the identification of environmentally sustainable VIP core materials for their further consideration in the design of the insulation concept. The results of the LCA are applied as one of several assessment metrics employed to develop the cryogenic insulation concept based on VIPs. To achieve this, various VIP core materials, namely, glass bubbles, expanded perlite, glass fibre, rigid polyurethane foam, silica aerogel, and fumed/pyrogenic silica, are compared under cryogenic vacuum conditions (78 K, 0.0133 Pa). Due to limited data availability for the core materials at liquid hydrogen temperatures, the temperature conditions adopted are those of liquid nitrogen. The functional unit is defined as the amount in kg of VIP core material required to provide a thermal resistance (R-value) of 1 m^2W/K for an area of 1 m^2 under cryogenic vacuum conditions (cold boundary temperature and warm boundary temperature (CBT/WBT) are 78 K and 293 K, respectively, vacuum pressure = 0.0133 Pa) and is expressed as:

$$FU[kg] = R\left[\frac{m^2K}{W}\right] \cdot \lambda\left[\frac{W}{mK}\right] \cdot \rho\left[\frac{kg}{m^3}\right] \cdot A\left[m^2\right] \tag{1}$$

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.

An overview of the core materials and the data used to calculate the reference flow is shown in Table 1. The data were obtained from experimental tests executed by Fesmire in Refs. [12,23], and Hunter et al. in Ref. [24].

The conventional core materials are chosen based on existing literature and commercially available VIPs, where they are either used as core materials for VIPs in the building sector or as insulating materials for evacuated insulation of cryogenic storage tanks. The system boundaries are presented in Fig. 4. As illustrated in the figure, the study spans the life cycle from cradle-to-grave, excluding the manufacturing and use of the VIP, and only accounting for the core materials' end-of-life treatment. The manufacturing of the VIP and its use are out of the scope of this study, as the focus is on the sustainability of the core materials. Here, the differences between manufacturing the VIP with different core materials are assumed to be negligible. The use phase is excluded as it does not involve energy consumption or emissions due to the defined functional unit, which assumes an equal thermal performance of the compared core materials. In addition, the convoluted nature of the degradability of VIP structures with different core materials, bring different risks and physical, mechanical, and chemical outcomes. The geographical location of the study is Europe; thus, the activities modelled in the life cycle inventory (LCI) are aimed at reflecting the conditions of this location.

B Life cycle inventory analysis

This subsection describes data collection and compilation to model the life cycle inventory. The life cycle inventory data are collected from the ecoinvent database (v.3.11, "cut-off") [25] and existing literature. The Activity Browser (AB) software is used to evaluate the environmental impacts of the different core materials, adopting the Environmental Footprint (EF) v. 3.1 method [26].

1) Raw material and manufacturing stages

The raw material and manufacturing stages for expanded perlite, glass fibre, and polyurethane foam are modelled directly using the ecoinvent database [25]. The raw material stage covers all resource-, energy-, waste-, and emission flows required to extract the raw materials, while the manufacturing stage here only covers the manufacture of the core materials from the extracted raw materials and any pre-products. A production activity is selected to model their core material production. The activities "expanded perlite production", "glass fibre production", and "polyurethane production, rigid foam" are chosen. Glass bubbles, aerogels, and fumed silica are not available in the database. Their foreground data is sourced from literature, while ecoinvent is employed for the background data.

A number of patents have been issued on the subject of hollow glass microspheres manufacturing (e. g. EP 0276921 B2, US patent 2,978,339, US patent 4,983,550, among others). The synthesis of glass bubbles can be achieved through various techniques such as flame synthesis, the liquid-droplet method, the dried gel process, or the electrical arc plasma method [27]. For the LCI modelling, an approach described in Ref. [19] is adapted, which assumes the flame synthesis method [19]. Accordingly, a production process for borosilicate glass tubes from Ref. [25] is replicated with modifications being made to the composition of the raw materials of the glass tubes to match that of the glass bubbles, which are composed of (in mass %) 70.0-80.0 % of SiO_2, 2.0-6.0 % of B_2O_3, 3.0-8.0 of Na_2O %, and 8.0-15.0 % of CaO (3 M Type K1, [19]). Additionally, a blowing agent (Na_2SO_4) with 0.3-0.6 mass % is required [27]. This implies that, except for the glass bubble raw materials and the agent, the other inputs and outputs of the process are approximated with those of the glass tube production, such as energy or waste flows. The necessity to follow this approach comes from the fact that apart from the one described in Ref. [19], no LCI for glass bubbles is, to the best of the

Table 1
Studied VIP core materials and their properties.

Insulation material	CBT/WBT [K]	Vacuum level [Pa]	Density [kg/m^3]	Thermal conductivity [mW/mK]	Data source	Reference flow [kg]
Glass bubbles	78/293	0.0133	65	0.700	[12]	4.55*10^{-2}
Expanded perlite	78/293	0.0133	132	0.950	[12]	0.125
Glass fibre	78/293	0.0133	16	1.972	[12]	3.155*10^{-2}
PUR foam	78/293	0.0133	42	7.750	[12]	0.326
Silica Aerogel	78/293	0.0133	152	1.304	[23]	0.198
Fumed silica[a]	76/304	0.0133	48	1.000	[24]	4.806*10^{-2}

[a] Due to limited data availability using fumed silica values at different CBT/WBT compared to other materials.

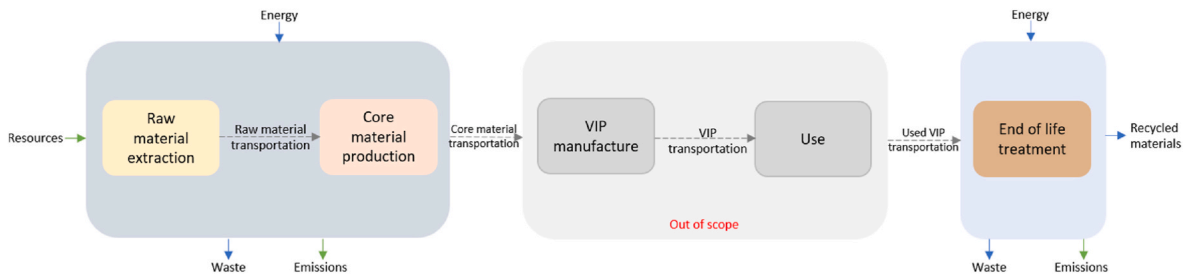

Fig. 4. System boundaries of the studied core material systems.

author's knowledge, publicly available. Details of the resulting inventory inputs on material and energy used can be found in Table 2.

The production of aerogels involves different raw materials and process technologies, which can cause significant variations in the LCIs and the resulting environmental impacts. Typical aerogel production involves gelation, ageing, and drying [28]. Silica aerogel blanket is the aerogel type considered in this study, as data on thermal conductivity under cryogenic vacuum conditions is available [23]. Supercritical drying is the technique employed for commercially available products [29], which is therefore the route modelled in this study. A detailed inventory for the production of a silica aerogel blanket manufactured via supercritical drying, based on data derived from experiments, is retrieved from Ref. [30] and used as the basis for the LCI model without further modifications. The inventory inputs are detailed in Table 2.

Fumed silica is modelled based on the best available techniques reference document by the European Commission [31]. The reported consumption and emission levels for synthetic amorphous pyrogenic silica are used to model the inventory, which includes raw material and energy consumption, direct process emissions and waste levels. The reported quantities are given as a range of consumption or emission, where the average of these ranges is used. Details of the inventory inputs are shown in Table 2.

Table 2
Details for the inventories of glass bubbles, silica aerogel, and fumed silica.

Core material	Inputs	Quantity	Unit
Glass bubbles	Silica	3.416*10^{-2}	kg/FU
	Boric oxide	1.822*10^{-3}	kg/FU
	Sodium oxide	2.505*10^{-3}	kg/FU
	Calcium oxide	5.238*10^{-3}	kg/FU
	Sodium sulphate	2.048*10^{-4}	kg/FU
	Aluminium oxide	2.275*10^{-3}	kg/FU
	Water	2.471*10^{-2}	kg/FU
	Electricity	5.142*10^{-2}	kWh/FU
	Heat	6.825*10^{-1}	MJ/FU
Silica aerogel	Tetraethyl orthosilicate	3.905*10^{-1}	kg/FU
	Ethanol	9.316*10^{-3}	kg/FU
	Water	2.380*10^{-1}	kg/FU
	Hydrochloric acid	6.006*10^{-3}	kg/FU
	Methyl ethyl ketone	1.261*10^{-2}	kg/FU
	Isopropanol	4.202*10^{-3}	kg/FU
	Hexamethyldisilazane	2.696*10^{-2}	kg/FU
	Polyethylene terephthalate	2.696*10^{-2}	kg/FU
	Polyethylene fleece	2.696*10^{-2}	kg/FU
	Ammonium hydroxide	4.321*10^{-2}	kg/FU
	Electricity	1.084*10^{1}	kWh/FU
Fumed silica	Hydrogen	4.325*10^{-3}	kg/FU
	Silicon tetrachloride	1.298*10^{-1}	kg/FU
	Electricity	2.203*10^{-1}	kWh/FU

2) Transportation

Several transportation steps are involved in the studied system: the transportation of raw materials to the core material manufacturing site, then to the VIP manufacturer, next to the user, and from the user to the end-of-life treatment facility. The transportation from raw material supplier to manufacturing site and from usage to EoL treatment is accounted for by using market activities, that represent a consumption mix of a region. These typically include transportation between producers and consumers as they account for the trade between producer and user [32]. Apart from that, there are no exact locations specified in this study, so it is assumed that all materials are transported the same distances and further transportation steps are neglected.

3) End-of-life stage

There are several options for end-of-life treatment. According to the European Waste Hierarchy, the preferred approach shall be prevention of waste generation, followed by re-use, recycling, (energetic) recovery, and, as a last resort, disposal [33]. Waste management of solids, which the VIP core materials are, usually undergoes four phases: first, the products reach the end of their useful lifetime and become waste. This is followed by the collection and transportation of the waste to a treatment facility. Lastly, the waste undergoes recycling, utilisation, or disposal [34].

Modelling the LCI of the end-of-life 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). Therefore, core materials that provide recycled materials at the end-of-life do not receive any credit [35].

The core materials enter the waste treatment chain as part of the VIP. Therefore, material separation and sorting are the first steps in the EoL treatment. The environmental impacts of this process are allocated to the core materials on a mass basis. This is done by modifying a process for sorting of building waste ("treatment of waste plaster-cardboard sandwich, sorting plant") from Ref. [25], by removing flows specific to the original composite and adding flows according to the core material in question. For the recyclable materials, namely glass fibre, glass bubbles, and fumed silica, the cut-off is after the sorting step, which is why no further treatment for them is modelled. They are available burden-free to any potential next user, meaning that no burden from the first use cycle of the material is allocated to its subsequent use cycles. It is, however, important to know that the recycling of the core materials can come with immense practical and economic challenges, as pointed out in Ref. [36]. One of these challenges was dust formation, which required precaution with regard to exhaust air filtration, as reported in Ref. [36]. For the non-recyclable materials, further treatment is accounted for, by adding flows to the modified treatment activity previously introduced. In the case of expanded perlite, it is assumed to be landfilled, as it cannot be incinerated due to its incombustible nature [37]. Further, it is impregnated with silicone [38] of which the removal via chemical recycling remains uncertain [39]. Landfilling is accounted for via the flow "market for inert waste", Europe from Ref. [25]. Rigid polyurethane foam is assumed to be landfilled and incinerated [40], which is accounted for with "market group for waste polyurethane", Europe from Ref. [25]. Aerogel is reused or landfilled, with a 15% to 85% share, respectively [41]. This is accounted for by adding "market for inert waste", Europe from Ref. [25], with an 85% share, to the modified treatment activity. The 15% of reusable aerogel is assumed to be useable as it is and is cut off.

C. Limitations

The inherent limitations of the study are presented in the following paragraphs. First, aspects regarding data quality and further sources of uncertainty specific to this study are addressed, followed by unaddressed flows and processes.

1) Data quality and uncertainty

The present study aims to facilitate the eco-design of an insulation concept during its early design phase. Consequently, the generation of further experimental data is lacking. Accordingly, the LCI was modelled using literature data and the ecoinvent database. Modelling the EoL stage incorporates an inherent uncertainty, as it occurs in the future. Furthermore, as the scope of the study is on the sustainability of the VIP core materials themselves, any sorting imperfections have not been accounted for. State-of-the-art waste treatment of VIPs has shown practical and economic challenges, as introduced in Section B.3, with ongoing research reported in Ref. [42], where a pre-treatment process of detecting and separating VIPs from refrigerators was developed. Currently, a project investigates the recycling of VIP support cores with the aim of developing a recycling process [43]. These aspects are addressed via the sensitivity study to increase the robustness of the results presented.

2) Unaddressed flows and processes

The transportation distances between core material manufacturing and VIP production, and from VIP manufacturing to point of use, are assumed to be equivalent for the materials being compared and are therefore excluded from the assessment. That notwithstanding, in comparative assessments, the exclusion of flows and processes is justifiable provided they are equivalent [34]. Due to the defined goal and scope of the present assessment, the VIP manufacturing and use phase are not considered. Therefore, aspects of mechanical stability and compaction of the materials due to thermal cycling during the use phase is beyond the scope of the present study.

D Life cycle impact assessment

The life cycle impact assessment (LCIA) is conducted according to the EF v. 3.1 method's 16 midpoint impact categories, which are presented in Table 3. This method is maintained by the European Commission and updated regularly [26]. The Activity Browser (v. 2.11.1) [44] software is used to conduct the LCIA. This involves first implementing the modelled LCIs into the software, followed by executing the calculation of a standard LCA using the EF method. The LCI data added to the AB is presented in the Appendix alongside the resulting impacts per impact category. The calculation is done for a standard reference flow of 1 kg with the results being scaled in the following to the reference flows shown Table 1.

E. Sensitivity study

Following the life cycle impact assessment of the various core materials, a sensitivity analysis involving several scenarios is conducted. The first three scenarios focus on the glass bubbles as these are the primary subject of the study. A fourth scenario explores the influence of the thermal conductivity on the environmental impacts, exemplified by the global warming potential. The scenarios investigated are:

- Scenario (Sc.) 1: Changing the European heat mix from natural gas to
  - o Sc. 1.1: Wood-chips based renewable heat (Germany)
  - o Sc. 1.2: Hard coal-based heat (European)
- Scenario (Sc.) 2: Changing the German electricity grid mix to
  - o Sc. 2.1: Wind, 1-3 MW turbine, onshore (Germany)
  - o Sc. 2.2: Hard coal-based electricity (Germany)
- Scenario (Sc.) 3: Closed-loop recycling of glass for glass bubbles: 27.5% of recycled material used in glass bubble manufacturing
- Scenario (Sc.) 4: Changing the thermal conductivity of the VIP core materials, glass fibre, glass bubbles, expanded perlite, and fumed silica, respectively, by
  - o -75%, −50%, −75%, 25%, 50%, 75%

Table 3
Impact categories covered in this study [26].

EF impact category	Impact category indicator	Unit
Climate change, total	Global warming potential (GWP100)	kg $CO_{2\ eq}$
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11 $_{eq}$
Human toxicity, cancer	Comparative toxic unit for humans (CTU_h)	CTUh
Human toxicity, non-cancer	Comparative toxic unit for humans (CTU_h)	CTUh
Particulate matter	Impact on human health	Disease incidence
Ionizing radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235} $_{eq}$
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC $_{eq}$
Acidification	Accumulated exceedance (AE)	mol H+ $_{eq}$
Eutrophication, terrestrial	Accumulated exceedance (AE)	mol N $_{eq}$
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P $_{eq}$
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N $_{eq}$
Ecotoxicity, freshwater	Comparative toxic unit for ecosystems (CTU_e)	CTUe
Land use	Soil quality index	Dimensionless
Water use	User deprivation potential (deprivation weighted water consumption)	m^3 water eq of deprived water
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb $_{eq}$
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

The first two scenarios with their sub-scenarios enable the investigation of the effects of renewable vs. non-renewable energy sources, while the third highlights the influence of reusing materials in the manufacture of glass bubbles. Assuming that 27.5% of recycled glass substitutes for virgin materials, this equates to the average of cullet that can be fed into the manufacture of borosilicate glass tubes (15-40% may be fed into the furnace) [45]. The fourth scenario addresses the limited data availability of thermal conductivity at liquid hydrogen temperatures. Hence, the sensitivity of the environmental impact of four core materials to changes in thermal conductivity is further investigated.

3. Results and discussion

This section presents the results of the life cycle assessment of the different core materials. It begins with the life cycle impact assessment to quantify the environmental impacts of the core materials and closes with a sensitivity analysis to account for variability.

A. Life cycle impact assessment

The normalized environmental impacts of the assessed core materials are shown in Fig. 5. Among them, silica aerogel and polyurethane foam exhibit the highest impacts across all categories. Silica aerogel has the highest impact in 13 out of 16 categories, while PUR foam has the highest score in the remaining 3 categories (material resources: metals/minerals, human toxicity: carcinogenic, eutrophication: marine). Each of the 16 impact categories is considered to be of equal importance, which is why the results indicate that silica aerogel, followed by PUR foam, are the least environmentally sustainable materials.

The findings demonstrate that the most environmentally friendly material is expanded perlite. It outperforms the remaining materials in 11 impact categories. It is followed by glass bubbles, which demonstrated better performance in water use, ozone depletion, and carcinogenic human toxicity, and glass fibre, which excelled in freshwater ecotoxicity and land use.

Apart from silica aerogel and PUR foam, fumed silica only exceeds certain materials in specific categories – for instance, it outperforms expanded perlite in ozone depletion potential, freshwater ecotoxicity, glass bubbles in land use, metals/minerals resources, and marine and terrestrial eutrophication as well as glass fibre in non-carcinogenic human toxicity and metals/minerals resources.

Silica aerogel and PUR foam are excluded from further in-depth analysis due to their comparatively poor environmental performance. For a more in-depth analysis (see Fig. 6), the impact categories that show the highest variation in score among the materials are studied. They include: water use, material resources: metals/minerals, ozone depletion, human toxicity: non-carcinogenic, land use, particulate matter formation, and eutrophication: terrestrial. In addition, global warming is included due to its societal relevance. The analysis is divided into stages, with each evaluated for its environmental impact.

The manufacturing stage is the main contributor to the environmental impact of both glass fibre and glass bubbles. For expanded perlite, the material extraction stage is the most significant. This is similar for the case of fumed silica for the majority of the impact categories. The end-of-life stage shows only minor contributions from each material to its overall impacts (see Fig. 6, and Table 4).

Fumed silica is the state-of-the-art core material employed in vacuum insulation panels [18]. From an environmental perspective, glass fibre, expanded perlite, or the proposed core material of glass bubbles outperforms fumed silica, which is shown by the thorough evaluation of the eight impact categories. It reveals that fumed silica is outperformed by expanded perlite in eight categories, by glass fibre in six, and by glass bubbles in five.

It should be noted that the conclusions presented here are made under the assumption that the stable physical structure, as well as the vacuum, is maintained, and the thermal performance as defined in the functional unit is fulfilled.

The EoL stage involves significant uncertainties, as modelling is based on current practices, which might not apply in the future or in a different location where the materials reach the end of their useful life.

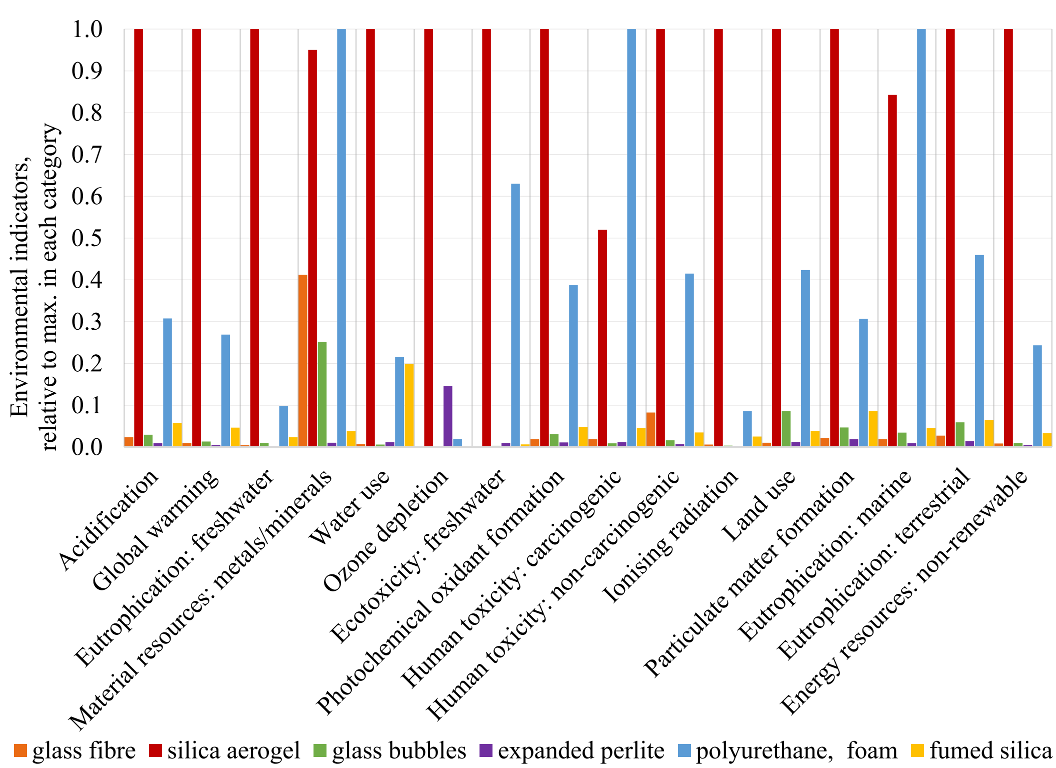

Fig. 5. Life cycle impact assessment results from cradle-to-grave of glass fibre, silica aerogel, glass bubbles, expanded perlite, polyurethane foam, and fumed silica as indicators relative to the maximum in each category, the maximum is set to 1 with the other values scaled accordingly.

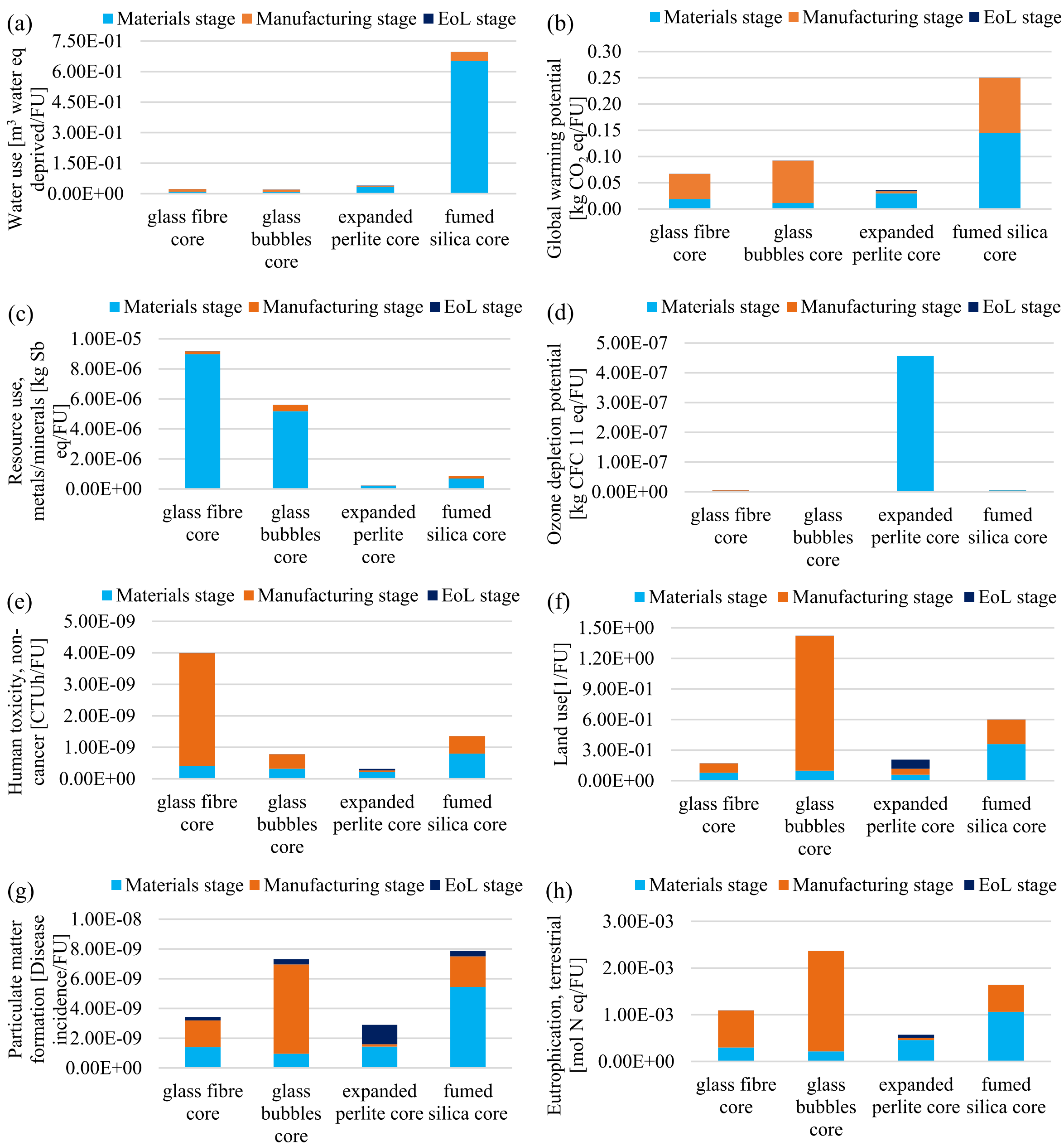

Fig. 6. Environmental impacts of selected core materials and impact categories per functional unit; with "Materials stage" relating to the (raw) material stage, "Manufacturing stage" to the respective stage, and "EoL stage" to the end-of-life stage; (a): Water use; (b): Global warming potential; (c): Material resources: metals/minerals; (d): Ozone depletion potential; (e): Human toxicity: non-carcinogenic; (f): Land use; (g): Particulate matter formation; (h): Eutrophication: terrestrial.

These are further detailed in Section 2.C.1). As studied in the sensitivity analysis, closed-loop recycling represents an ideal, but unlikely, route [22].

Currently, the manufacturing of hollow glass microspheres from recycled glass might pose some challenges due to the need to meet certain specific mechanical properties when employed as a VIP core material [46]. This is not the case for glass fibre, as up to about 80% of recycled glass can be used in glass fibre production [47]. It is highly advantageous to use secondary glass, either from internal recycling or external sources, as it reduces the amount of virgin material needed and reduces the energy consumption for melting. However, as it has been reported for the glass bubbles, it is not feasible for every glass product to incorporate secondary materials in its manufacture [45].

Recycling of expanded perlite can be accomplished by chemically removing its hydrophobic impregnation layer made of silicone [39], allowing the reusability of the material. However, chemical recycling of silicone remains to be developed on an industrial scale [39]. Nevertheless, use cases of waste expanded perlite include its application as a lightweight cementitious composite, which comes with a reduced thermal conductivity [48], and its utilisation in the production of geopolymers [49]. There is also the potential for PUR foam and silica aerogel recycling options to be more viable and circular in the future [40,50]. While chemical recycling of PUR foam can be advantageous from an environmental perspective when compared to conventional treatment routes such as incineration or landfill, its implementation into commercial-scale chemical recycling facilities is still under development [40]. Chemical recycling of aerogels comes with the advantage of using the EoL products for the production of new polymers. However, this requires high temperatures, leading to high energy consumption and process costs, but it avoids the detrimental effects of silica volatile

Table 4
Impacts over the whole life cycle of chosen impact categories of the more in-depth studied core materials.

Material/impact category	Glass fibre	Glass bubbles	Expanded perlite	Fumed silica
Water use [m^3 water eq of deprived water/FU]	$2.30*10^{-2}$	$1.98*10^{-2}$	$3.97*10^{-2}$	$6.96*10^{-1}$
Climate change [kg $CO_{2\ eq}$/FU]	$6.68*10^{-2}$	$9.21*10^{-2}$	$3.63*10^{-2}$	$2.50*10^{-1}$
Resource use: metals/minerals [kg Sb $_{eq}$/FU]	$9.18*10^{-6}$	$5.59*10^{-6}$	$2.27*10^{-7}$	$8.56*10^{-7}$
Ozone depletion [kg CFC-11 $_{eq}$/FU]	$4.80*10^{-9}$	$2.00*10^{-9}$	$4.56*10^{-7}$	$6.12*10^{-9}$
Human toxicity: non-cancer [CTUh/FU]]	$3.99*10^{-9}$	$7.80*10^{-10}$	$3.14*10^{-10}$	$1.35*10^{-9}$
Land use [1/FU]	$1.71*10^{-1}$	1.42	$2.06*10^{-1}$	$6.01*10^{-1}$
Particulate matter [Disease incidence/FU]	$3.43*10^{-9}$	$7.31*10^{-9}$	$2.90*10^{-9}$	$7.87*10^{-9}$
Eutrophication: terrestrial [mol N $_{eq}$/FU]	$1.09*10^{-3}$	$2.36*10^{-3}$	$5.73*10^{-5}$	$1.64*10^{-3}$

compounds that can occur in landfills. Silica volatile compounds can deposit as part of landfill gas in pipelines, which comes with consequences on engine and turbine performance [50].

B. Sensitivity study

First, a sensitivity analysis is carried out using glass bubbles as a case study. In addition, the sensitivity of the thermal conductivity of the four more in-depth studied core materials – glass fibre, glass bubbles, expanded perlite, and fumed silica – is examined using the global warming potential as a baseline impact category. The detailed scenarios investigated can be found in Section II.E.

As previously stated, the manufacturing stage of glass bubbles has the highest environmental impact. Hence, the first sensitivity analysis focuses on different energy sources. The results show that switching to fully renewable electricity based on 100% wind power has the potential to improve the overall environmental performance, which is not necessarily the case in all impact categories for the considered renewable heat source (see Figs. 7 and 8). Specifically, the global warming potential is reduced by 25% using renewable electricity (Sc. 2.1) and 31% using renewable heat (Sc. 1.1), but land use increased by 62% in the latter case. As previously stated, all considered impact categories are treated as being of equal importance. It is not valid to state that, for instance, the increased land use impact due to renewable heat can be outweighed by the reduced global warming impact. No significant impact increase for hard-coal-based electricity and heat sources is found when compared to the current mix.

The influence of the circularity of glass bubbles is examined through closed-loop recycling in the third scenario. The results showed improvements across all categories, with the most notable being a 25% reduction in material resources: metals/minerals (see Figs. 7 and 8). This is as expected, given that there will be less virgin material input.

A sensitivity analysis is conducted to assess the impact of variations in thermal conductivity of the more in-depth studied core materials, namely glass fibre, glass bubbles, expanded perlite, and fumed silica. It is undertaken due to the limited data available on the thermal conductivity of the core materials under study. Therefore, the implications of a change in thermal conductivity are investigated on the impact category of climate change, with the results presented in Fig. 9.

Fig. 9 shows the influence of varying the thermal conductivity of the investigated materials on the environmental impact, in this case, global warming potential. As indicated in Fig. 9, the influence of varying the thermal conductivity is negligible for materials with low environmental burden. This is observed in the case of expanded perlite. However, as the environmental impact increases, the influence of a change in thermal conductivity becomes more pronounced. This is exemplified in the case of fumed silica. Hence, the analysis on the case of global warming potential indicates that the lower the environmental impact of a material, the lower is the influence of a change in thermal conductivity on its impacts. Consequently, it is important to emphasise the potential variability in the responses of materials to changes in thermal conductivity when transitioning from liquid nitrogen to liquid hydrogen conditions.

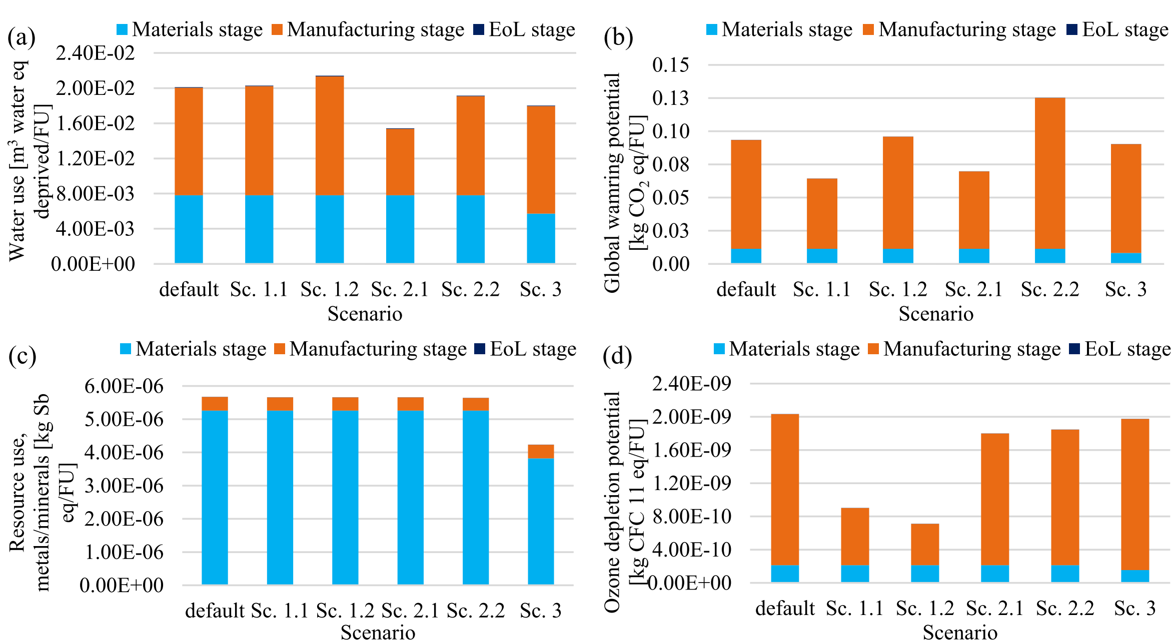

Fig. 7. Sensitivity analysis of the different Scenarios, Sc. 1.1 – Sc. 3 of selected impact categories per functional unit; (a): Water use; (b): Global warming potential; (c): Material resources: metals/minerals; (d): Ozone depletion potential.

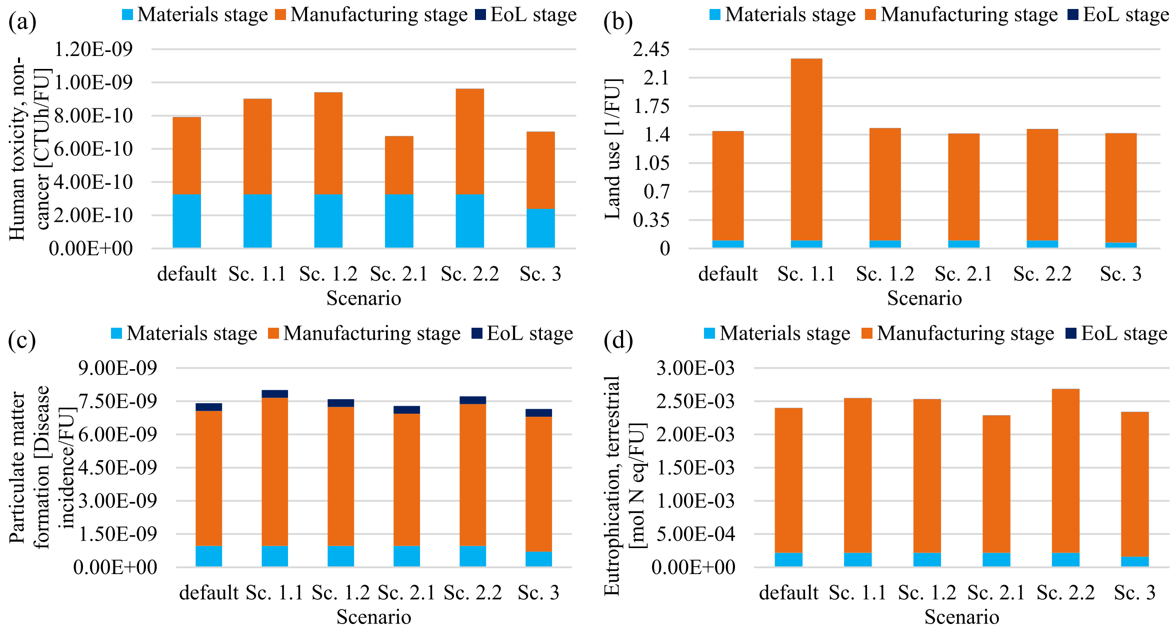

Fig. 8. Sensitivity analysis of the different Scenarios, Sc. 1.1 – Sc. 3 of selected impact categories per functional unit; (a): Human toxicity: non-carcinogenic; (b): Land use; (c): Particulate matter formation; (d): Eutrophication: terrestrial.

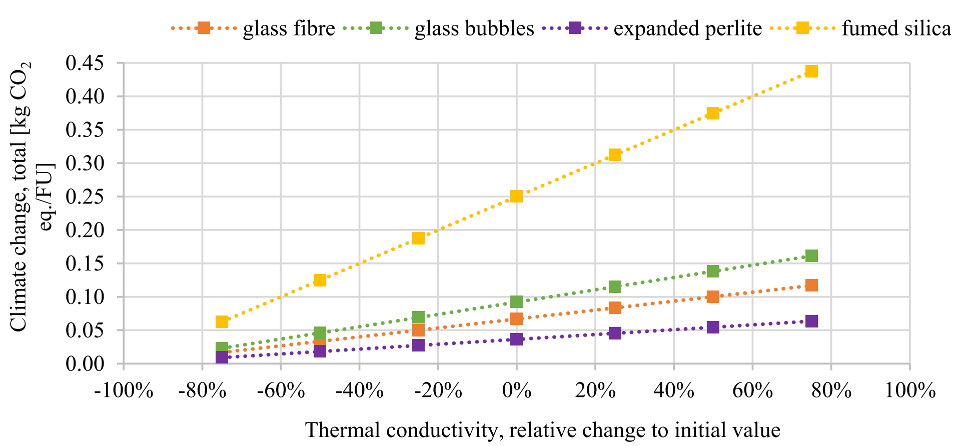

Fig. 9. Sensitivity analysis on the influence of a change in thermal conductivity on the global warming impact of the core materials, showing the total life cycle impacts, including the default value at 0%.

4. Conclusion

The environmental sustainability of six different vacuum insulation panel core materials for liquid hydrogen storage tank insulation was the focus of this study. The framework of life cycle assessment was employed to identify the least and most environmentally friendly core material. A comparative, attributional assessment, covering the entire life cycle from cradle-to-grave, was performed. Furthermore, the circularity of the core materials was evaluated based on different end-of-life treatment options. Six different materials were assessed, starting from their raw material extraction and manufacturing, to their end-of-life treatment and recyclability. The following conclusions were drawn from the work:

- Silica aerogel and rigid polyurethane foam were found to exhibit the highest environmental impacts among the six materials compared under given conditions.
- Silica aerogel and rigid polyurethane foam were also among the most challenging from a circularity perspective.
- The in-depth analysis showed that:
  - o Expanded perlite demonstrated superior performance in the majority of impact categories, which is followed by glass fibre, glass bubbles, and fumed silica.
- The best options from a circularity perspective were the glass-based materials.
- The environmental performance can potentially be improved by using a fully renewable electricity source and adopting closed-loop recycling.
- The change in environmental impact due to a variation in thermal conductivity is lower for materials that exhibit a lower environmental impact.

Lastly, the selection of the most appropriate core material requires more than an assessment of its environmental performance. Consideration also needs to be given to other requirements, such as thermal and mechanical performance.

CRediT authorship contribution statement

Hannah Sauer: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Bright E. Okpeke:** Writing – review & editing, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Agnieszka S. Dzielendziak:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Robert Eberwein:** Writing – review & editing, Funding acquisition. **Lars Baetcke:** Writing – review & editing, Supervision. **Sören Ehlers:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2026.153937.

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