



## **NICOLHy - Novel Insulation Concepts for LH<sub>2</sub> Storage Tanks**

Project deliverable

D5.1 Life Cycle Assessment of novel insulation concepts

|                              |                                                           |
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| Contributors                 |                                                           |
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## The NICOLHy Consortium:

| Participant No. | Short name | Country |
|-----------------|------------|---------|
| 1 (Coordinator) | BAM        | Germany |
| 2               | UniBo      | Italy   |
| 3               | DLR        | Germany |
| 4               | NTNU       | Norway  |
| 5               | NTUA       | Greece  |

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**Abbreviations:**

|                 |                                                             |
|-----------------|-------------------------------------------------------------|
| A               | Area                                                        |
| AB              | Activity Browser                                            |
| ANSI            | American National Standards Institute                       |
| BAT             | Best available technique                                    |
| BREF            | Best available technique reference document                 |
| BoM             | Bill of material                                            |
| CBT             | Cold boundary temperature                                   |
| GHG             | Greenhouse gas                                              |
| EF              | Environmental footprint method                              |
| EoL             | End of life                                                 |
| EPS             | Expanded polystyrene foam                                   |
| FU              | Functional unit                                             |
| H <sub>2</sub>  | Hydrogen                                                    |
| HGM             | Hollow glass microspheres / glass bubbles                   |
| KPI             | Key Performance Indicator                                   |
| LCA             | Life cycle assessment                                       |
| LCI             | Life cycle inventory                                        |
| LCIA            | Life cycle impact assessment                                |
| LH <sub>2</sub> | Liquid hydrogen                                             |
| M               | Manufacturing stage                                         |
| MLI             | Multilayer insulation                                       |
| NICOLHy         | Novel insulation concepts for LH <sub>2</sub> storage tanks |
| PUR             | Polyurethane foam                                           |
| R               | Thermal resistance                                          |
| RM              | (Raw) material stage                                        |
| Sc.             | Scenario                                                    |
| t               | Thickness                                                   |
| TRL             | Technology readiness level                                  |
| VIP             | Vacuum insulation panel                                     |
| WBT             | Warm boundary temperature                                   |
| $\lambda$       | Thermal conductivity                                        |
| $\rho$          | Density                                                     |

# 1 Introduction

As the world transitions toward sustainable energy sources, hydrogen ( $H_2$ ) has emerged as a pivotal energy carrier for decarbonizing the supply to industry, mobility, and society. It facilitates the storage of electricity produced from renewable sources, such as wind power, solar power, or geothermal energy, in the form of chemical energy. Hydrogen in its free form can be stored and transported either as a gas or a liquid. It exhibits a significantly higher density in its liquefied state. Considering the same storage volume, it allows increasing the storage capacity of more than 100% with respect to compressed  $H_2$  at 70 MPa. Liquid hydrogen ( $LH_2$ ) is particularly relevant to applications with limited space, such as long-distance transportation via ships or in heavy-duty mobility applications. However, the storage of  $LH_2$  presents considerable challenges, due to the requirement to keep it at a low temperature of 20 K [1]. It is therefore essential to ensure that heat inputs remain at a minimum. Any  $LH_2$  boil-off must be managed appropriately in order to avoid over-pressurisation and energy losses in the tank. This requires storage tanks with thermal superinsulation and a design that limits any means of heat transfer from the environment [2]. Currently, double-walled tanks with an evacuated thermal insulation material in between these walls are utilised. The insulation material may be based on bulk material like expanded perlite, silica particles, or glass bubbles (hollow glass microspheres/HGMs), or on layers such as multilayer insulation systems (MLLI) [3]. A novel concept, which enables a modular, open-form, and time efficient manufacturing of a multiple-failure tolerant onshore and offshore cryogenic  $LH_2$  storage tank is currently under development. This concept considers the utilisation of vacuum insulation panels (VIPs) to serve the purpose of thermal superinsulation. The main components of VIPs are a highly porous core material and a gas-impermeable envelope [4]. There has been significant research conducted on VIPs for the construction sector, including thermo-mechanical aspects, as well as environmental considerations [5], [6], [7]. However, research on the environmental sustainability of VIPs as cryogenic insulation is limited. To avoid the shift of environmental burdens and to ensure the sustainability of the hydrogen supply chain, from its production, via storage, to its utilisation, it is essential that any novel concepts which promote the development of such a supply chain are studied from an environmental perspective.

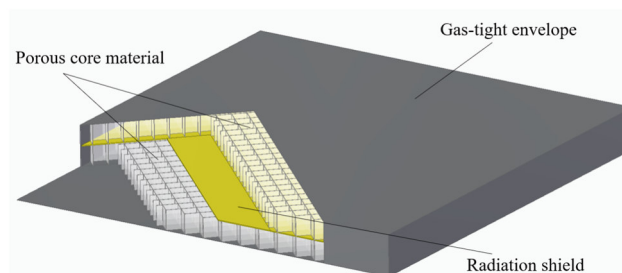
Therefore, the aim of this deliverable is to provide a comprehensive environmental performance assessment to evaluate the environmental sustainability of the novel insulation concept for the storage of  $LH_2$ . The life cycle assessment (LCA) methodology is employed to assess six distinct VIP core materials, followed by a novel and a conventional VIP, and conventional cryogenic insulation materials. The most environmentally sustainable VIP core material is identified, and the novel VIP concept is benchmarked with a conventional VIP and with conventional insulation materials, respectively. All life cycle stages are considered, from raw material extraction to end-of-life. The assessment exclusively studies the aspect of environmental sustainability. Other aspects, such as thermal and mechanical performance, must be considered when designing an insulation concept for cryogenic storage tanks, however, these are beyond the scope of this deliverable.

## 2 Method and Materials

The aim of this work is to demonstrate the sustainability of the NICOLHy concept. This is done by evaluating the environmental performance of the developed concept through the standardized life cycle assessment framework (ISO 14040 and 14044). The life cycle assessment framework is a well-established method for assessing the environmental performance of a product or service throughout its lifetime. The study is primarily performed as an attributional LCA focused on evaluating the environmental impacts of the NICOLHy VIP, and comparing it with conventional VIPs and insulation materials. This is carried out under vacuum and cryogenic conditions as the insulation is intended for liquid hydrogen storage tank.

### 2.1 Description of the novel insulation concept

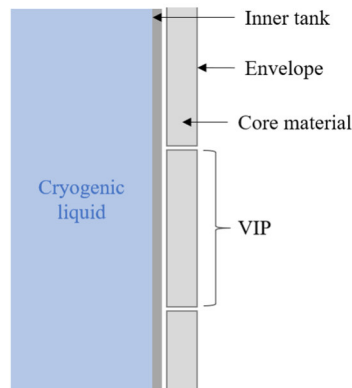
The insulation concept under development is based on vacuum insulation panels (VIPs). VIPs consist of an evacuated, rigid, highly porous core material, which is encased in a gas-impermeable envelope. Their properties can be further enhanced by the incorporation of additional components such as getters, desiccants, and/or opacifiers. Potential core materials comprise polyurethane foam, aerogels, fumed silica, or glass fibre, while the envelope may be constructed from aluminium or a metalized polymer layer. Silica gel is a typical desiccant, while synthetic zeolite may be employed as getter. As demonstrated in Figure 1, a radiation shield can be utilised as an opacifier. An example of an opacifier for the state-of-the-art core material fumed silica is silicon carbide [8].



*Figure 1: Schematic of an example of a vacuum insulation panel*

Hollow glass microspheres (HGMs/glass bubbles) have been identified as a promising core material for VIPs in the cryogenics sector. They have demonstrated superior performance compared to the state-of-the-art bulk insulation material in the cryogenics sector, i.e. perlite [9]. Stainless steel is regarded as a promising envelope material, due to its suitability for cryogenic hydrogen environments [10]. Hence, the proposed concept involves glass bubbles as the core material and stainless steel as the envelope foil.

Figure 2 provides a visual representation of a proposed configuration for the arrangement of the VIPs in relation to the cryogenic liquid tank.



*Figure 2: Schematic of the concept of vacuum insulation panels for insulating a cryogenic liquid tank*

The VIPs acts as the insulation, thereby maintaining the temperature of the liquid stored within the inner tank.

## 2.2 Applied methodology

The standardized LCA methodology (ISO 14040 and 14044) is employed to quantify the potential environmental impact of the VIP [11]. This is done by mapping all material and energy flows from each process in the life cycle of the VIP. These flows are then linked to impacts on the environment. In this way, the environmental impact of different options can be quantified and compared, which in turn gives information on how the environment and the human health will be affected by our choices. Its main characteristics are the life cycle perspective it takes, the coverage of a broad range of environmental issues, being quantitative, and science based. Assessing all stages of a product system from resource extraction, production, use, and disposal allows to prevent burden-shifting, i.e. lowering environmental impacts in one life cycle stage and identifying if this would increase impacts in another stage. The quantitative nature allows comparing impacts of different processes and product systems. Emissions are translated into impacts using characterization models, which are rooted in natural science [12].

The LCA framework involves four phases namely, goal and scope definition, inventory analysis, impact assessment and interpretation (Figure 3). The four phases of the methodology are used in this study. Firstly, the goal and scope are identified. This sets the context for the assessment. Furthermore, what is to be compared is established, both in terms of the comparable unit and the system boundaries. The aim of this step is to describe the product system as well as the purpose of the study and includes the reason(s) of carrying out the study, intended application(s), target audience, limitations due to methodological choices, functional unit and the system boundaries.

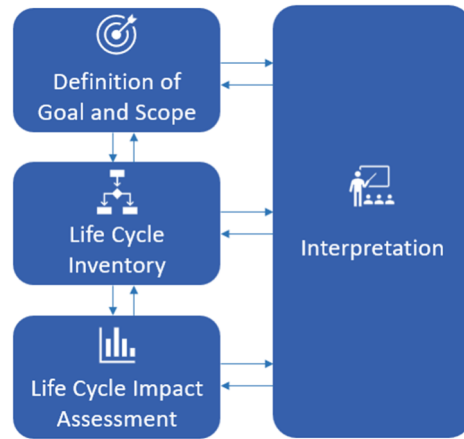


Figure 3: Four phases of an LCA, adopted from ISO 14040 [13]

In the inventory analysis phase, a system flow model specifying and quantifying the material and energy flows between the different activities from cradle to grave is developed. The analysis involves data collection and forms the basis for calculations. Based on the results of the inventory analysis, the potential environmental impacts are then evaluated for the product system throughout the life cycle during the impact assessment phase. The impacts are categorized based on what they affect in the environment and varies depending on the type of impact assessment methodology employed. Common methodologies used include, ReCiPe, CML, Ecoindicator, Environmental footprint (EF), and so on. The basic principle adopted by these methodologies is the same: everything crossing the system boundary (emissions, energy, materials) is added together based on how much they affect a specific category of impact compared to a reference emission/substance. The LCIA is commonly performed with LCA tools/software, where the relevant impact categories and characterization factors have already been incorporated. In this study, the activity browser (v. 2.11.1) software is used for impact assessment. Finally, the results from LCI and LCIA are interpreted in the interpretation phase in accordance to the stated goal and scope. This step includes completeness, sensitivity and consistency checks [14]. This ensures that everything is coherent. Based on the results, recommendations are provided and conclusions are drawn.

LCA often involves some assumptions of the context investigated and the technologies adopted. On that note, a sensitivity analysis is performed to determine the robustness of the assessment and identify assumptions which may drastically change the results of the study. This is done by varying the input parameters to identify which parameter has the most influence on the result. A Monte-Carlo Simulation is performed to analyse data uncertainties. In the following sections and subsections, in-depth details on the applied method and sensitivity analysis are presented.

## 2.3 Goal and scope definition

This section outlines the goal and scope of the NICOLHy concept presented in this report. This includes common and case specific aspects of the scope (e.g. the functional unit, the system boundaries, general data sources and data quality), as well as specific and cross-cutting limitations and assumptions.

### 2.3.1 Goal definition

The goal definition sets the context of the LCA study and forms the foundation for the scope of the study [12]. According to ISO 14040/44, the following points have to be clearly stated to define the goal of a life cycle assessment:

- The intended application,
- The reasons for carrying out the study,
- The target audience, i.e. to whom the results of the study are intended to be communicated,
- Whether the results are intended to be used in comparative assertions intended to be disclosed to the public

#### *Reasons for carrying out the study*

The European Union targets climate neutrality by 2050, implying net zero greenhouse gas (GHG) emissions [15]. One key to achieving this target is green hydrogen, produced from renewable electricity via water electrolysis. It can decarbonize hard-to-electrify sectors, such as long-distance transport or heavy industry [16]. The hydrogen supply chain begins with production, followed by storage, transport, delivery, and ultimately utilisation [1]. Green hydrogen is regarded as sustainable. However, the aforementioned aspects of the supply chain fall short in that regard. Focusing on the aspect of storage, the NICOLHy project aims to develop a novel sustainable insulation concept for the storage of cryogenic liquid hydrogen. Hence, it is important to identify and assess the life cycle phases and processes that contribute most to the overall environmental impact of the insulation concept. This enables the identification of hot spots and can lead to recommendations for improvements.

#### *Intended application of the study*

The LCA study is a comparative life cycle assessment of the environmental impacts of different insulation concepts from cradle to grave. The assessment explores different VIP concepts based on various core and envelope materials and their corresponding environmental impact to guide decision makers. Consequently, the results are intended to support decision making when investing in LH2 storage tanks and for regulatory bodies regarding the potential of reducing climate and environmental impact along hydrogen value chain.

#### *Target audience*

The main target audiences include European stakeholders, decision and policy makers, maritime industries, academia, environmentalists and the general public. Aggregated results will be disclosed to the public and the most interesting results from a scientific perspective will be used to compile manuscripts for academic publishing and presented at scientific conferences.

#### *Comparative assertions*

The study compares various insulation concepts, including the novel VIP, conventional VIPs, and conventional insulation materials. The following materials are included in the comparative assessment:

Table 1: Materials included in the comparative assessment

| <b>VIP core materials</b>                                                                               | <b>Reason to include in the comparative assessment</b>           |
|---------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| Type K1 hollow glass microspheres (glass bubbles) <sup>a</sup>                                          | Identified in [17] to be employed as VIP core material           |
| Synthetic amorphous pyrogenic silica (pyrogenic/fumed silica) <sup>a</sup>                              | Identified in [8] to be employed as VIP core material            |
| Glass fibre                                                                                             | Identified in [8] to be employed as VIP core material            |
| Spray-on rigid polyurethane foam (polyurethane / PUR foam) <sup>a</sup>                                 | Identified in [8] to be employed as VIP core material            |
| Expanded perlite                                                                                        | Identified in [8] to be employed as VIP core material            |
| Silica aerogel blanket (silica aerogel) <sup>a</sup>                                                    | Identified in [8] to be employed as VIP core material            |
|                                                                                                         |                                                                  |
| <b>VIP concept's components</b>                                                                         | <b>Reason to include in the comparative assessment</b>           |
| Glass bubble core                                                                                       | Tested as insulation material in [18] and [9]                    |
| Steel foil envelope                                                                                     | Stainless steel 316L is feasible for cryogenic applications [10] |
| Fumed silica                                                                                            | Considered a conventional core material [8]                      |
| Trilaminate foil                                                                                        | Typical envelope material [7]                                    |
|                                                                                                         |                                                                  |
| <b>Conventional insulation materials for cryogenic applications</b>                                     | <b>Reason to include in the comparative assessment</b>           |
| Glass fibre                                                                                             | Tested for cryogenic insulation applications [19]                |
| Polyurethane foam                                                                                       | Used as cryogenic insulation [20]                                |
| Expanded perlite                                                                                        | Used as cryogenic insulation [9]                                 |
| Silica aerogel blanket                                                                                  | Tested for cryogenic insulation applications [19]                |
| Double-aluminized Mylar with polyester net spacer insulation (multilayer insulation / MLI) <sup>a</sup> | Conventional cryogenic insulation [9]                            |
| Expanded polystyrene foam (EPS foam) <sup>a</sup>                                                       | Used as LNG tank insulation [21]                                 |

<sup>a</sup> The term(s) in parentheses are used throughout the report.

In summary, the goal of the current LCA study is to comparatively assess the environmental sustainability of different insulation concepts for liquid hydrogen storage tanks with a focus on VIPs.

#### *Limitations due to methodological choices*

The LCA is site-unspecific, implying that the results can for instance not be used to inform a decision on a specific site. In the life cycle inventory (LCI), market activities are employed for activities in the background system, representing the average consumption of the chosen region [22], i.e. the European Union.

#### 2.3.2 Functional unit and reference flow

To compare different insulation concepts and materials, a quantitative unit called the functional unit needs to be defined. This unit represents the function of the product system i.e., what is specifically compared, and this unit has to be the same for the different product system (insulation concepts). The function investigated in this study is the insulation of a cryogenic LH<sub>2</sub> tank. This function can be fulfilled via conventional insulation materials or via VIPs. The

former fulfils its functions solely with its insulating properties. The latter, however, requires an additional, here called sub-function, to fulfil the main function, which is the encasing of the VIP core material by an envelope material. The envelope does not fulfil the function of insulation; however, it is essential for the function of the VIP as an insulation material. In the following, the functional unit is defined in two stages. Firstly, the insulation properties that must be met are specified. Secondly, the sub-function required for the VIPs is defined.

The functional unit for the insulation of the LH<sub>2</sub> tank is defined as the amount in kg of insulation material (VIP or conventional insulation) required to provide a thermal resistance (R-value) of 20 m<sup>2</sup>W/K for an area of 1 m<sup>2</sup> under cryogenic conditions (CBT=78 K, WBT=293 K) and is expressed as:

$$FU [kg] = R [m^2 K/W] * \lambda [W/mK] * \rho [kg/m^3] * A [m^2].$$

Where:

R: thermal resistance of the core material

$\lambda$ : thermal conductivity of the core material

$\rho$ : density of the core material

A: area that is covered by the core material

The VIP core materials are studied under vacuum pressure (0.0133 Pa), whereas the conventional insulation materials are studied under ambient pressure. This approach is adopted because the VIPs are in and of themselves not under vacuum, only their core is. Hence, for a fair comparison, the conventional insulation materials are investigated under ambient pressure.

As previously stated, to fulfil the function of insulation, VIPs require a core material, and an envelope. The envelope encases the core and maintains the vacuum [4]. Due to limited data availability, the envelope flows for the steel foil and trilaminate foil are quantified differently. The amount of steel foil required to encase the VIP core is defined by the following formulation:

$$Steel\ envelope [kg] = t [m] * \rho_{steel} [kg/m^3] * A_{envelope} [m^2].$$

Where:

t: thickness of steel foil (0.15 mm)

$\rho_{steel}$ : density of steel

$A_{envelope}$ : area the envelope covers

With regard to the trilaminate foil, the amount required is obtained from [7] and can be found in Table 2.

Table 2: Studied VIP envelope materials and their properties

| VIP / envelope material                 | Core material thickness [m] | Envelope area [m <sup>2</sup> ] | Density [kg/m <sup>3</sup> ] | Flow [kg] |
|-----------------------------------------|-----------------------------|---------------------------------|------------------------------|-----------|
| Glass bubbles VIP – steel envelope      | 0.014                       | 2.056                           | 8000                         | 2.467     |
| Fumed silica VIP – trilaminate envelope | 2.076                       | 2.080                           | -                            | 0.3       |

The reference flow is the quantity to which all other in- and output flows of the processes, that are part of the system's life cycle, are quantitatively related to [12]. Here, the reference flow

equals the mass of the insulation concepts under study. These are the amount of conventional insulation material, or VIP core and envelope material, respectively. The reference flow of each investigated material is presented in Table 3, jointly with the data used for their quantification.

*Table 3: Studied insulation materials and their properties*

| Insulation material                             | CBT/WBT [K] | Vacuum level [Pa] | Density [kg/m <sup>3</sup> ] | Thermal conductivity [mW/mK] | Reference flow [kg]   |
|-------------------------------------------------|-------------|-------------------|------------------------------|------------------------------|-----------------------|
| Glass bubbles – VIP core                        | 78/293      | 0.0133            | 65                           | 0.700 [23]                   | 9.10*10 <sup>-1</sup> |
| Fumed silica – VIP core <sup>b</sup>            | 76/304      | 0.0133            | 48                           | 1.000 [24]                   | 9.61*10 <sup>-1</sup> |
| Glass fibre – VIP core                          | 78/293      | 0.0133            | 16                           | 1.972 [23]                   | 6.31*10 <sup>-1</sup> |
| PUR foam – VIP core                             | 78/293      | 0.0133            | 42                           | 7.750 [23]                   | 6.51                  |
| Expanded perlite – VIP core                     | 78/293      | 0.0133            | 132                          | 0.095 [23]                   | 2.51                  |
| Silica aerogel – VIP core                       | 78/293      | 0.0133            | 152                          | 1.304 [25]                   | 3.96                  |
| Glass fibre – conv. insulation                  | 78/293      | Ambient           | 16                           | 25.99 [23]                   | 8.32                  |
| PUR foam – conv. insulation                     | 78/293      | 0.0133            | 42                           | 21.17 [23]                   | 17.78                 |
| Expanded perlite – conv. insulation             | 78/293      | Ambient           | 132                          | 34.95 [23]                   | 92.27                 |
| Silica aerogel – conv. insulation               | 78/293      | 0.0133            | 152                          | 13.40 [25]                   | 40.74                 |
| MLI (16 mm thick, 40 layers) - conv. insulation | 78/293      | 0.0133            | 42 <sup>c</sup>              | 17.40 [26]                   | 14.62                 |
| EPS - conv. insulation                          | 78/293      | ambient           | 32.04                        | 9.000 [27]                   | 5.767                 |

<sup>b</sup> Due to limited data availability, using fumed silica values at different CBT / WBT compared to other materials.

<sup>c</sup> Due to limited data availability, using the density of a similar MLI (double-aluminized mylar and polyester net spacer, 4.9 mm thick, 10 layers)

### 2.3.3 System boundaries

The system boundaries define elements included in the LCA study and those not considered in the assessment. The cradle-to-grave approach is applied to the environmental assessment of the insulation concepts. This approach considers impacts at each stage of the life cycle of a product, from raw material extraction and processing, through all subsequent stages of manufacturing, transportation, use, and end-of-life. The LCI modelling framework applied is attributional. A distinction needs to be made between the different VIP concepts and the conventional insulation materials, as they differ by materials and processes involved.

An overview of the system boundaries of the studied VIP concepts is visualised in Figure 4.

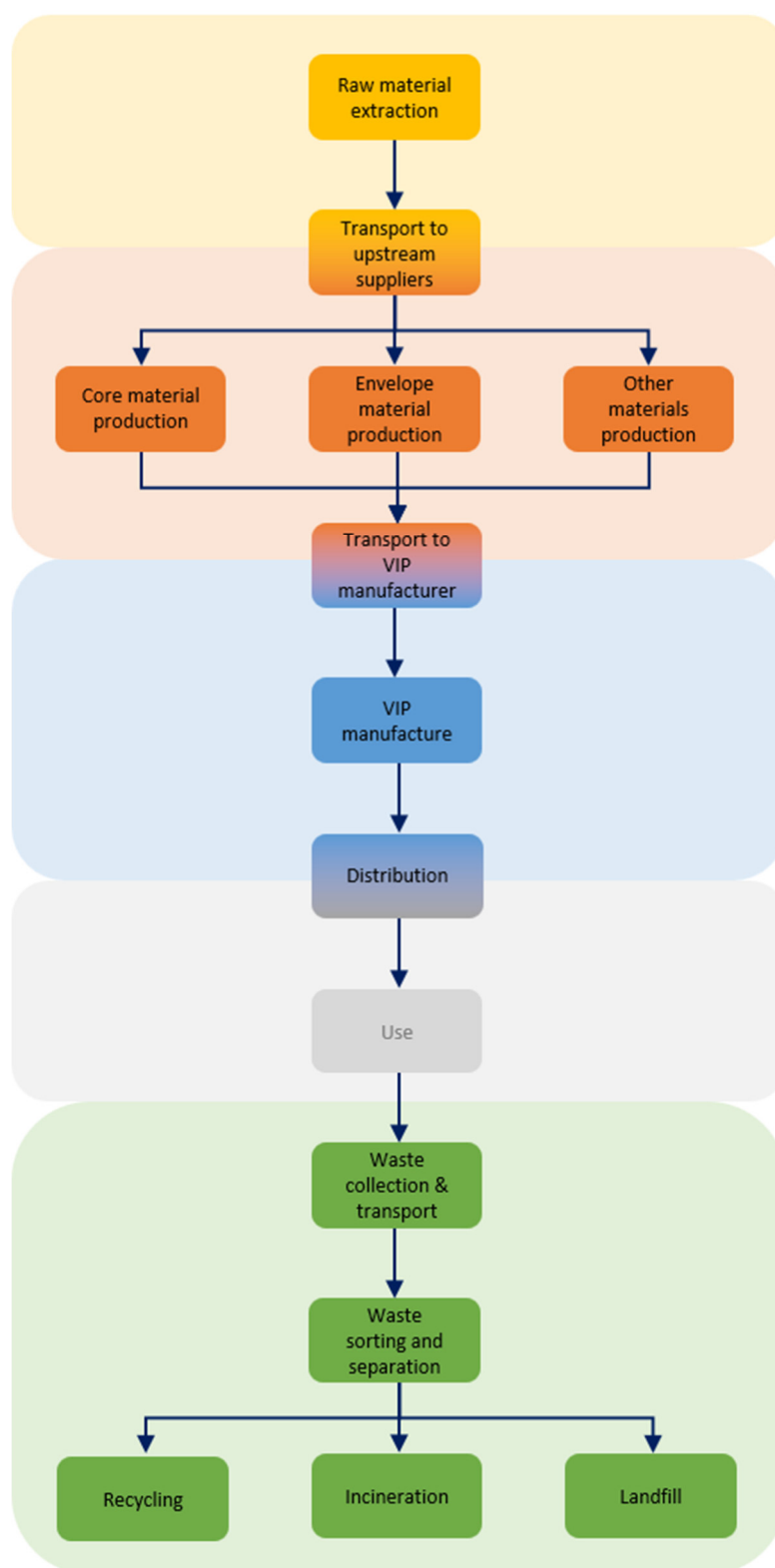


Figure 4: System boundary of the VIP concepts

As previously stated, the system boundaries differ in terms of the materials and processes involved. Considering the different VIPs, except for the material dependent stages of raw material extraction and end-of-life treatment, the processes involved are similar. Manufacturing of a VIP involves several steps. If the core is a loose powder, it may be mixed with additional components, such as opacifiers, followed by pressing the panel into a moulding tool. In further

steps, the core is dried, wrapped in the envelope, and finally evacuated to result in the VIP [28]. The use stage is out of scope as there are no energy or resource inflows and waste or emission outflows. It shall be noted, that the use of capital goods is considered, which means that the use of machinery and equipment is regarded. 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.

A generic visualisation of the conventional insulation materials system boundaries is presented in Figure 5.

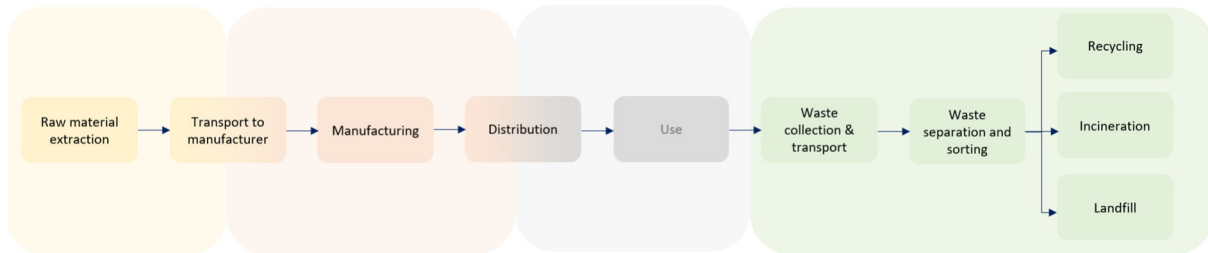


Figure 5: System boundary of the conventional insulation materials

The same scope applies for the different conventional insulation materials, which implies that the use stage is excluded from the assessment. The remaining life cycle stages are considered in the assessment. Furthermore, the use of capital goods is considered, as is the case for the VIPs.

#### 2.3.4 Allocation

The recommended method for solving multifunctionality, i.e. processes with more than one product output (by-products), in the attributional framework is allocation. However, the ILCD guideline recommends system expansion alongside allocation. Allocation is performed by dividing the inputs and outputs of the multifunctional process between the different products or functions, e.g. on a mass or market price basis. System expansion is accomplished by expanding the system with the most likely alternative process providing the secondary product and in case of substitution this process is subtracted from the system [12]. In Section 2.4 the LCI modelling is presented, which includes specifications about the allocations that are applied.

The background database employed (ecoinvent v.3.11, “cut-off” [29]) differentiates between allocatable, recyclable, and waste products. The former are ordinary by-products and are – as the naming indicates – handled via allocation [30].

#### 2.3.5 Data quality

Due to the study being site-unspecific, i.e. not for a specific company or location, data is collected from inventory databases and credible (scientific) sources. This includes papers, reports from research projects, best available technique reference documents, governmental reports, and the aforementioned ecoinvent database. Since the product system considered in the current study – the novel insulation concept – lies in the future, high data quality cannot be guaranteed. To increase the robustness of the results compiled with these data sources, sensitivity and uncertainty analyses are conducted.

## 2.4 Life cycle inventory

In this subsection, the data collection to model the LCI is presented. Existing literature and the ecoinvent database (v.3.11, “cut-off”) are employed to conduct this task. Collected data is organized utilising Excel and transferred to the Activity Browser (AB) (v. 2.11.1) software [31] to quantify the environmental impacts (see Section 2.5).

### 2.4.1 VIP core materials

In the following, the raw material extraction, manufacturing, transportation, and end-of-life stages are presented in detail for the VIP core materials. Data sources and modelling assumptions are provided. The core materials under investigation are glass bubbles, fumed silica, glass fibre, silica aerogel, expanded perlite, and polyurethane foam, as presented in Subsection 2.3.1.

### Raw material and manufacturing stages

The extraction and processing of all upstream raw materials and energy are covered by the raw material stage, while the product manufacture is covered by the manufacturing stage. These stages are considered jointly here. A brief description of these stages for the considered core materials is presented below.

**Glass bubbles** have multiple industrial applications ranging from fillers in plastic components, paints or coatings to insulation for cryogenic storage tanks [32], [23]. However, the quantification of the environmental impact of their production remains a scarcely investigated topic, to the best of the authors’ knowledge. A number of production modes have been identified through a review of extant literature and patent documentation. These comprise flame synthesis, the liquid-droplet method, the dried gel process, and the electrical arc plasma method [33]. Relevant patents on the production include EP 0276921 B2, US patent 2,978,339, and US patent 4,983,550, among others. In the current study, the flame synthesis production mode of glass bubble is modelled, with the approach from [34] being adapted. Consequently, an inventory for the manufacture of borosilicate glass tubes from [29] is replicated, with adjustments being made to the material requirements of the glass bubbles under investigation (3M Type K1, [34]). This includes a specific raw material composition in addition of Na<sub>2</sub>SO<sub>4</sub> as the blowing agent [33]. This approach is based on the assumption that the production of glass bubbles equates to energy, material, and waste flows of glass tube production, with the exception of the modifications described. Details of the resulting LCI can be found in Table 4.

*Table 4: LCI data for glass bubble materials and manufacturing stage, showing only the flows modified to match the glass bubble’s composition in addition to electricity and heat flows; remaining flows are from the ecoinvent activity “glass tube production, borosilicate, DE” and are not presented here*

| amount                | unit | product/biosphere flow                               | activity/compartments                                           | location                   |
|-----------------------|------|------------------------------------------------------|-----------------------------------------------------------------|----------------------------|
| 1.00                  | kg   | glass bubbles                                        | glass bubbles production                                        |                            |
| 4.00*10 <sup>-2</sup> | kg   | boric oxide                                          | market for boric oxide                                          | GLO                        |
| 7.51*10 <sup>-1</sup> | kg   | silica sand                                          | market for silica sand                                          | GLO                        |
| 5.50*10 <sup>-2</sup> | kg   | soda ash, light                                      | market for soda ash, light                                      | RER                        |
| 1.15*10 <sup>-1</sup> | kg   | limestone, milled, packed                            | market for limestone, milled, packed                            | Europe without Switzerland |
| 4.50*10 <sup>-3</sup> | kg   | sodium sulfate, anhydrite                            | market for sodium sulfate, anhydrite                            | RoW                        |
| 1.13                  | kWh  | electricity, medium voltage                          | market for electricity, medium voltage                          | DE                         |
| 1.20*10 <sup>1</sup>  | MJ   | heat, district or industrial, natural gas            | market for heat, district or industrial, natural gas            | Europe without Switzerland |
| 3.03                  | MJ   | heat, district or industrial, other than natural gas | market for heat, district or industrial, other than natural gas | Europe without Switzerland |

**Fumed or pyrogenic silica** can be regarded as the state-of-the-art core material for VIPs [4]. Other potential areas for application include coatings, adhesives, sealants, cosmetics, or care products [35]. Fumed silica particles are produced by the introduction of volatile chlorosilanes and/or methylchlorosilanes into a reactor along with hydrogen and air. At high temperatures between 1200 and 1600°C, the silanes undergo hydrolysis, resulting in the formation of SiO<sub>2</sub> molecules. These molecules then undergo a process of particle formation, followed by aggregation and ultimately agglomeration.

Fumed silica is a well-known product in the European chemical industry, and the present consumption and emission levels of its production are provided in the Best Available Technique (BAT) Reference Document (BREF) on Large Volume Inorganic Chemicals. The consumption of raw materials and energy, in addition to emission levels and waste generation, are outlined in detail [36]. These are downscaled on a per kg level for the LCI and constitute the main data source for this study. In addition, machinery utilised in the production process is also considered. This is approximated with an activity from [29], with an estimation similarly based on [29] for its quantity. The resulting inventory is presented in Table 5.

Table 5: LCI data for pyrogenic silica material and manufacturing data

| amount                 | unit | product/biosphere flow            | activity/compartments                        | location                   |
|------------------------|------|-----------------------------------|----------------------------------------------|----------------------------|
| 1                      | kg   | pyrogenic silica                  | pyrogenic silica production                  |                            |
| 9.00*10 <sup>-2</sup>  | kg   | hydrogen, gaseous, low pressure   | hydrogen production, steam methane reforming | RER                        |
| 2.70                   | kg   | silicon tetrachloride             | market for silicon tetrachloride             | RoW                        |
| -1.00*10 <sup>-2</sup> | kg   | inert waste, for final disposal   | market for inert waste, for final disposal   | CH                         |
| 4.58                   | kWh  | electricity, medium voltage       | market group for electricity, medium voltage | Europe without Switzerland |
| -2.00*10 <sup>-3</sup> | kg   | hazardous waste, for incineration | market for hazardous waste, for incineration | Europe without Switzerland |
| 6.40*10 <sup>-1</sup>  | kg   | carbon dioxide, fossil            | air                                          |                            |
| 5.00*10 <sup>-5</sup>  | kg   | chlorine                          | air                                          |                            |
| 1.00*10 <sup>-4</sup>  | kg   | hydrochloric acid                 | air                                          |                            |
| 4*10 <sup>-10</sup>    | unit | chemical factory, organics        | chemical factory construction, organics      | RER                        |

The LCIs of the VIP core materials - expanded perlite, glass fibre, and PUR - are modelled based on available activities in ecoinvent database. These activities are presented in Table 6.

Table 6: Activities selected from the ecoinvent database for the LCI of the material and manufacturing stage of glass fibre, PUR foam, and expanded perlite

| activity                            | product                  | location | database              |
|-------------------------------------|--------------------------|----------|-----------------------|
| glass fibre production              | glass fibre              | RER      | ecoinvent-3.11-cutoff |
| polyurethane production, rigid foam | polyurethane, rigid foam | RER      | ecoinvent-3.11-cutoff |
| expanded perlite production         | expanded perlite         | CH       | ecoinvent-3.11-cutoff |

In the case of *silica aerogel*, and *MLI*, data from literature is employed for modelling the foreground system, while ecoinvent [29] is utilised for the background system. The potential applications of aerogels are extensive, with one of such applications being a core material of VIPs [4]. Aerogels are materials with low density and high porosity making them excellent low thermal conductivity insulation options. Furthermore, there are numerous other potential applications of aerogels, such as in the food and biomedical sectors. Researchers explore various combinations of raw materials, energy sources, and manufacturing techniques, all of which typically involve gelation, ageing, and drying. Depending on their composition, aerogels can be categorized as inorganic, organic, or hybrid in nature. As demonstrated in the literature, the environmental impacts of aerogels show variability, attributable to the various types and production modes of these materials [37]. From [23] thermal conductivity data under cryogenic conditions is available for a silica aerogel blanket. Consequently, an LCI for this type of aerogel

is modelled in the current study. An inventory of a silica aerogel blanket produced via atmospheric and supercritical drying is available in literature [38], with the latter being the production mode employed for commercially available products [39]. In this work, the LCI based on supercritical drying is adapted and remodelled - refer to Table 7 for the resulting inventory.

Table 7: LCI data for silica aerogel material and manufacturing stage

| amount                 | unit | product/biosphere flow                                             | activity/compartments                                                         | location                   |
|------------------------|------|--------------------------------------------------------------------|-------------------------------------------------------------------------------|----------------------------|
| 1.00                   | kg   | silica aerogel                                                     | silica aerogel production                                                     |                            |
| 1.11                   | kg   | tap water                                                          | market for tap water                                                          | Europe without Switzerland |
| 4.70*10 <sup>-2</sup>  | kg   | ethanol, without water, in 99.7% solution state, from fermentation | market for ethanol, without water, in 99.7% solution state, from fermentation | GLO                        |
| 1.36*10 <sup>-1</sup>  | kg   | fleece, polyethylene                                               | market for fleece, polyethylene                                               | GLO                        |
| 3.03*10 <sup>-2</sup>  | kg   | hydrochloric acid, without water, in 30% solution state            | market for hydrochloric acid, without water, in 30% solution state            | RER                        |
| 2.12*10 <sup>-2</sup>  | kg   | isopropanol                                                        | market for isopropanol                                                        | RER                        |
| 6.36*10 <sup>-2</sup>  | kg   | methyl ethyl ketone                                                | market for methyl ethyl ketone                                                | RER                        |
| 1.36*10 <sup>-1</sup>  | kg   | polyethylene terephthalate, granulate, amorphous                   | market for polyethylene terephthalate, granulate, amorphous                   | GLO                        |
| 1.97                   | kg   | tetraethyl orthosilicate                                           | market for tetraethyl orthosilicate                                           | GLO                        |
| 9.09*10 <sup>-2</sup>  | kg   | water, completely softened                                         | market for water, completely softened                                         | RER                        |
| 1.36*10 <sup>-1</sup>  | kg   | hexamethyldisilazane                                               | market for hexamethyldisilazane                                               | GLO                        |
| 2.18*10 <sup>-1</sup>  | kg   | ammonium hydroxide                                                 | ammonium hydroxide                                                            | GLO                        |
| 4.00*10 <sup>-10</sup> | unit | chemical factory, organics                                         | chemical factory construction, organics                                       | RER                        |
| 5.47*10 <sup>1</sup>   | kWh  | electricity, medium voltage                                        | market group for electricity, medium voltage                                  | US                         |

## Transportation stage

The system's life cycle includes the following transportation steps: transportation of the raw materials to the manufacturing of upstream product flows, delivery to the production site of the VIP core material, subsequent transportation of the core material to the VIP manufacture, and finally, shipment to the end-of-life treatment plant. The novel concept under study is of low technology readiness level (TRL), implying that the specific locations of manufacture, use, and end-of-life (EoL) treatment remain to be defined. Nonetheless, by the use ofecoinvent's market activities, transportation from raw material supply to manufacturing and from usage to the treatment of end-of-life materials, are accounted for [22]. For the other transportation steps, the same distances are assumed and therefore omitted in the inventory modelling.

## End-of-life stage

As the materials reach the end of their useful life, the resulting waste must undergo treatment. This suggests that the process of waste treatment occurs at an unknown point in the future, thereby introducing an inherent element of uncertainty to the model. Nonetheless, the waste treatment is modelled based on the current practices.

The following general modelling provisions are considered due to the database employed. The responsibility for the management of waste materials lies with the generator of the waste in question. Recycled materials only bear the impact of the recycling process and are available burden-free to the next user [30].

To understand the EoL stage of the VIP core materials, it is necessary to examine the VIP as a whole. Currently, there are no commercial-scale VIP recycling facilities [7]. A study was conducted to investigate the recycling of fridges and refrigerators insulated with VIPs. The

study revealed that the core and envelope materials were sorted in the polyurethane-output category [40]. Furthermore, it was stated in [7] that the panels developed were recyclable at the end of their useful life. A range of recycling rates for the core material was also investigated [7]. For the product system under study, it is evident that waste treatment of the VIP occurs in the future, due to the cryogenic tank's lifetime. Therefore, the following assumption is made with regard to the EoL stage of the VIP core: the VIPs are subjected to a process of recycling in a sorting and separation step, with 100% of core material recycling.

The inventory of the initial sorting and separation step is approximated with a modified activity from [29]. The environmental impacts of this process are allocated to the core materials on a mass basis. Details can be found in Table 8.

Table 8: LCI data for dismantling the VIP

| amount                 | unit           | product/biosphere flow                         | activity/compartments                     | location |
|------------------------|----------------|------------------------------------------------|-------------------------------------------|----------|
| 1.00                   | m <sup>2</sup> | VIP components for further treatment/recycling | VIP disassembly                           |          |
| 3.70*10 <sup>-3</sup>  | kWh            | electricity, low voltage                       | market group for electricity, low voltage | CH       |
| 1.11*10 <sup>-3</sup>  | m <sup>3</sup> | excavation, hydraulic digger                   | excavation, hydraulic digger              | RER      |
| 1.00*10 <sup>-10</sup> | unit           | sorting facility, for construction waste       | sorting facility, for construction waste  | CH       |

The core materials - glass bubbles, fumed silica, and glass fibre - are recyclable, thus no further treatment is required; they are cut-off from further life cycle considerations. However, two aspects of perlite complicate its recycling. These aspects are: its incombustibility [41], and its silicone impregnation [42], leading to its most probable treatment being that of landfilling. Silica aerogel is subjected to reuse with a share of 15%, while the remaining 85% is assumed to be disposed of via landfill [43]. The management of polyurethane foam waste typically involves incineration and disposal in landfill [44]. The LCI data of the EoL management is presented in Table 9.

Table 9: LCI data of the VIP core materials end-of-life stage

| amount | unit | product/biosphere flow                | activity/compartments                            | location |
|--------|------|---------------------------------------|--------------------------------------------------|----------|
| -1.00  | kg   | glass for recycling                   | glass for recycling                              |          |
| -1.00  | kg   | glass cullet, sorted                  | glass cullet, sorted, Recycled Content cut-off   | GLO      |
| -1.00  | kg   | fumed silica for recycling            | fumed silica for recycling                       |          |
| -1.00  | kg   | silica fume, densified                | silica fume, densified, Recycled Content cut-off | GLO      |
| -1.00  | kg   | expanded perlite to landfill          | expanded perlite to landfill                     |          |
| -1.00  | kg   | inert waste                           | market for inert waste                           | RER      |
| -1.00  | kg   | silica aerogel to reuse/landfill      | silica aerogel to reuse/landfill                 |          |
| -0.85  | kg   | inert waste                           | market for inert waste                           | RER      |
| -0.15  | kg   | silica aerogel, for reuse             | silica aerogel, for reuse                        |          |
| -1.00  | kg   | polyurethane to landfill/incineration | polyurethane to landfill/incineration            |          |
| -1.00  | kg   | waste polyurethane                    | market group for waste polyurethane              | RER      |

#### 2.4.2 NICOLHy concept

The following sections outline the raw material and manufacturing stages, transportation, and end-of-life stage for the novel VIP developed within the NICOLHy project. This VIP is composed of glass bubbles (as core material) and stainless-steel foil (as envelope material). Relevant data sources and modelling assumptions are also presented.

#### Raw material extraction and manufacturing stages

In this section, the extraction and processing of all upstream raw materials and energy used in the production of the NICOLHy VIP concept is elucidated. Also, the manufacturing process of the VIP concept is explained as well. Both stages – raw material extraction and manufacturing – are jointly considered here.

The NICOLHy VIP concept is composed of glass bubbles core material. Their LCI is described in Subsection 2.4.1. The envelope material selected for the VIP concept under development in the NICOLHy project is stainless steel 316L. Two activities from [29] are employed for modelling the inventory of the steel foil. The first activity involves the production of stainless steel, while the second activity estimates its subsequent processing. For details, please refer to Table 10.

*Table 10: LCI data for the steel foil materials and manufacturing stage*

| amount | unit | product/biosphere flow                 | activity/compartments                             | location |
|--------|------|----------------------------------------|---------------------------------------------------|----------|
| 1.00   | kg   | steel foil envelope                    | steel foil production                             |          |
| 1.00   | kg   | steel, chromium steel 18/8, hot rolled | market for steel, chromium steel 18/8, hot rolled | GLO      |
| 1.00   | kg   | sheet rolling, chromium steel          | market for sheet rolling, chromium steel          | GLO      |

As highlighted in Section 2.1, additional constituents of a VIP can include desiccants, getters, opacifiers [8], or even sensors. In the current phase of the NICOLHy project, these constituents are yet to be specifically defined. To investigate their potential environmental impacts, those delineated in [7] are applied and added to the inventory of the VIP. These are shown in Table 11 and are referred to as “other VIP components” throughout the report.

*Table 11: LCI data for further components of the VIP*

| amount               | unit | product/biosphere flow                                                 | activity/compartments                                                  | location |
|----------------------|------|------------------------------------------------------------------------|------------------------------------------------------------------------|----------|
| 1.15                 | kg   | VIP additional components                                              | VIP additional components                                              |          |
| $3.00 \cdot 10^{-3}$ | kg   | printed wiring board production, surface mounted, unspecified, Pb free | market for printed wiring board, surface mounted, unspecified, Pb free | GLO      |
| $1.50 \cdot 10^{-4}$ | kg   | fibre, cotton                                                          | market for fibre, cotton                                               | GLO      |
| 1.00                 | kg   | magnetite                                                              | market for magnetite                                                   | GLO      |
| $1.50 \cdot 10^{-1}$ | kg   | fleece, polyethylene                                                   | market for fleece, polyethylene                                        | GLO      |

The inventory of manufacturing the VIP is approximated with an equivalent amount of electricity obtained from [7]. In addition, machinery utilised in the VIP manufacturing process is also considered. As an approximation, an activity from [29] is included with an estimation similarly based on [29]. Further details can be found in Table 12.

*Table 12: LCI data for manufacturing the VIP*

| amount             | unit           | product/biosphere flow      | activity/compartments                        | location                   |
|--------------------|----------------|-----------------------------|----------------------------------------------|----------------------------|
| 1.00               | m <sup>2</sup> | NICOLHy VIP                 | VIP assembly                                 |                            |
| 7.00               | kWh            | electricity, medium voltage | market group for electricity, medium voltage | Europe without Switzerland |
| $4 \cdot 10^{-10}$ | unit           | building machine            | building machine production                  | RER                        |

## Transportation stage

With regard to the transportation stage, the assumptions employed in modelling the core materials are also applied to the NICOLHy VIP, with the exemption that the envelope materials and other VIP components are additionally transported to the VIP manufacturing facility along with the core materials. For further details, please refer to Subsection 2.4.1.

## End-of-life stage

The same generic modelling assumptions as stated in Subsection 2.4.1 for the EoL stage of the core materials apply to the NICOLHy VIP.

As described in the subsection, the first step in the EoL stage of a VIP is sorting and separation. The same modelling provisions as presented apply for the whole VIP, with the only exemption that no allocation on the VIP core's mass basis is required. The whole VIP undergoes this initial sorting and separation step.

The glass bubble core material is recyclable, with its LCI modelling presented in Subsection 2.4.1. The envelope material under investigation, steel foil, is also recyclable. Consequently, steel is cut-off from the system, becoming available to subsequent users without any associated burden. Details of the modelled inventory can be found in Table 13.

*Table 13: LCI data of the end-of-life stage of steel foil*

| amount | unit | product/biosphere flow          | activity/compartments | location |
|--------|------|---------------------------------|-----------------------|----------|
| -1.00  | kg   | steel for recycling             | steel for recycling   |          |
| -1.00  | kg   | market for iron scrap, unsorted | iron scrap, unsorted  | GLO      |

A simplified approach is applied for the end-of-life treatment of the other VIP components. It is assumed, that these other VIP components are incinerated. To reflect the environmental burdens of this procedure, an activity from [29] for the incineration of municipal solid waste is chosen, as it accounts for a variety of materials, that are incinerated. The chosen dataset can be seen in Table 14.

*Table 14: Activities selected from the ecoinvent database for the LCI of the EoL treatment of other VIP components*

| activity                               | product               | location | database              |
|----------------------------------------|-----------------------|----------|-----------------------|
| market group for municipal solid waste | municipal solid waste | RER      | ecoinvent-3.11-cutoff |

An overview of the resulting LCI for one NICOLHy VIP is presented in Table 15, with the amounts scaled according to the reference flow (refer to Subsection 2.3.2).

*Table 15: Overview of the LCI of the NICOLHy VIP, scaled to the reference flow*

| amount | unit           | product/biosphere flow                         | activity/compartments     |
|--------|----------------|------------------------------------------------|---------------------------|
| 0.91   | kg             | glass bubbles                                  | glass bubbles production  |
| 2.47   | kg             | steel foil envelope                            | steel foil production     |
| 1.15   | kg             | VIP additional components                      | VIP additional components |
| 1.00   | m <sup>2</sup> | NICOLHy VIP                                    | VIP assembly              |
| 1.00   | m <sup>2</sup> | VIP components for further treatment/recycling | VIP disassembly           |
| -1.00  | kg             | glass for recycling                            | glass for recycling       |
| -1.00  | kg             | steel for recycling                            | steel for recycling       |
| -1.15  | kg             | market group for municipal solid waste         | municipal solid waste     |

### 2.4.3 Conventional vacuum insulation panel

In the following, the raw material extraction, manufacturing, transportation, and end-of-life stages for a conventional VIP composed of a fumed silica core and a trilaminate envelope are presented. The data sources and modelling assumptions are also explained.

#### Raw material extraction and manufacturing stages

The core material for the conventional VIP is composed of fumed silica. The LCI is described in Subsection 2.4.1.

Trilaminate foil is typically used as a conventional envelope material for VIPs. The material and energy requirements presented in [7] are remodelled for the inventory of the trilaminate foil, with details shown in Table 16.

Table 16: LCI data for the trilaminate foil materials and manufacturing stage

| amount | unit | product/biosphere flow                   | activity/compartments                               | location                   |
|--------|------|------------------------------------------|-----------------------------------------------------|----------------------------|
| 1.00   | kg   | trilaminate foil envelope                | trilaminate foil production                         |                            |
| 0.235  | kg   | methyl ethyl ketone                      | market for methyl ethyl ketone                      | RER                        |
| 0.039  | kg   | methylene diphenyl diisocyanate          | market for methylene diphenyl diisocyanate          | RER                        |
| 0.624  | kg   | packaging film, low density polyethylene | market for packaging film, low density polyethylene | GLO                        |
| 0.078  | kg   | polyol                                   | market for polyol                                   | RER                        |
| 1.765  | kWh  | electricity, medium voltage              | market group for electricity, medium voltage        | Europe without Switzerland |
| 0.024  | kg   | sheet rolling, aluminium                 | sheet rolling, aluminium                            | RER                        |
| 0.024  | kg   | aluminium, wrought alloy                 | market for aluminium, wrought alloy                 | GLO                        |

Other constituents of the conventional VIP are identical to those of the NICOLHy VIP. Their corresponding LCIs can be found in Subsection 2.4.2, Table 11.

### Transportation stage

The assumptions employed in the modelling of the NICOLHy VIP also apply to the conventional VIP. For further details, please refer to Subsection 2.4.22.4.2.

### End-of-life stage

The same generic modelling assumptions as stated in Section 2.4.2 for the end-of-life stage modelling apply to the conventional VIP. Furthermore, the first step in the EoL stage of the conventional VIP is identical to the NICOLHy VIP – the sorting and separation step. Refer to Subsection 2.4.2 for further details.

The core material, fumed silica, is recyclable, with its EoL modelling presented in Subsection 2.4.1.

The end-of-life of the envelope material, the trilaminate, is modelled with an activity from [29], which comprises the management of mixed waste plastics. It includes the treatment pathways of incineration and landfill, with their respective shares based on the European market. It is assumed that a proportion of the aluminium present in the trilaminate foil is recovered after incineration, with a rate of 9% [45]. Details of the modelled inventory can be found in Table 17.

Table 17: LCI data of the end-of-life stage of trilaminate foil

| amount                 | unit | product/biosphere flow                                   | activity/compartments          | location |
|------------------------|------|----------------------------------------------------------|--------------------------------|----------|
| -1.00                  | kg   | trilaminate                                              | trilaminate                    |          |
| -1.00                  | kg   | market group for waste plastic, mixture                  | waste plastic, mixture         | RER      |
| -2.12*10 <sup>-3</sup> | kg   | aluminium scrap, post-consumer, Recycled Content cut-off | aluminium scrap, post-consumer | GLO      |

The other components of the VIP undergo EoL treatment as well. The same modelling approach as for the NICOLHy VIP is followed, details are presented in Subsection 2.4.2.

#### 2.4.4 Conventional insulation materials

As introduced in Subsection 2.3.1, the following materials are investigated in the current study as conventional insulation materials: expanded perlite, polyurethane foam, MLI, silica aerogel, glass fibre, and polystyrene foam. The system boundaries for the conventional insulation materials are highlighted below.

#### Raw material extraction and manufacturing stage

The VIP core materials - expanded perlite, polyurethane foam, silica aerogel, and glass fibre - are insulation materials in and of themselves. Therefore, their LCIs are the same as those introduced in Section 2.4.1.

The LCI of the conventional insulation material EPS, is modelled with an activity that is available in ecoinvent database and shown in Table 18.

*Table 18: Activities selected from the ecoinvent database for the LCI of the material and manufacturing stage of glass fibre, PUR foam, and expanded perlite*

| activity                           | product                 | location | database              |
|------------------------------------|-------------------------|----------|-----------------------|
| polystyrene production, expandable | polystyrene, expandable | RER      | ecoinvent-3.11-cutoff |

In the case of MLI, data from literature is employed for modelling the foreground system, while ecoinvent [29] is utilised for the background system.

Evacuated cryogenic multilayer insulation systems are typically employed for the storage, transfer, or thermal protection of cryogenic liquids. Their utilisation is often dictated by the specific requirements associated with a given application, such as thickness or weight limitations [23]. The design of MLIs is characterised by the integration of evacuated, layered, highly-reflective foils, which are separated by the utilisation of spacer materials [26]. The production of MLI for low-temperature applications usually include the following steps: material cutting, laying, quilting, cutting of the quilted material, outer surface film application, and finally, grounding component installation [46]. However, the quantification of the environmental impact of the manufacture of MLI foils remains a scarcely investigated topic, to the best of the authors' knowledge. According to [26], a Bill of Material (BoM) for a 30 layered double-aluminized Mylar insulation is available. In addition, the aforementioned manufacturing steps from [46] are utilised to quantify their inventory, drawing on data from literature and the ecoinvent database. The resulting inventory is shown in Table 19. Furthermore, the quilting operations are approximated with data derived from [47], for the sewing of home furnishing textiles as an equivalent amount of electricity consumption ( $4.91 \cdot 10^{-2}$  kWh/kg). The approximation of cutting operations is facilitated by an LCI from [48] for laser cutting of textiles, and presented in Table 20. Also, the BoM shows that the spacer is composed of a knit woven polyester yarn. In view of the fact that the ecoinvent database currently contains non-woven textile entries, a modified ecoinvent weaving process is employed to account for the weaving of the spacer. The inventory of the modified operation is presented in Table 21.

*Table 19: LCI data for MLI foil material and manufacturing stage*

| amount                | unit | product/biosphere flow                                 | activity/compartments                                             | location |
|-----------------------|------|--------------------------------------------------------|-------------------------------------------------------------------|----------|
| 1.00                  | kg   | multi-layer insulation foil                            | multi-layer insulation foil production                            |          |
| 8.78*10 <sup>-2</sup> | kg   | aluminium, wrought alloy                               | market for aluminium, wrought alloy                               | GLO      |
| 3.55*10 <sup>-1</sup> | kg   | textile production, nonwoven polyester, needle-punched | market for textile production, nonwoven polyester, needle-punched | GLO      |
| 8.78*10 <sup>-2</sup> | kg   | sheet rolling, aluminium                               | market for sheet rolling, aluminium                               | GLO      |
| 5.48*10 <sup>-2</sup> | kg   | zeolite powder                                         | market for zeolite, powder                                        | GLO      |
| 5.34*10 <sup>-1</sup> | kg   | packaging film production, low density polyethylene    | market for packaging film production, low density polyethylene    | GLO      |
| 3.23*10 <sup>-1</sup> | kg   | M: MLI weaving of synthetic fibre, for industrial use  | M: MLI weaving of synthetic fibre, for industrial use             | GLO      |
| 4.91*10 <sup>-2</sup> | kWh  | electricity, medium voltage                            | market group for electricity, medium voltage                      | RER      |
| 3.55*10 <sup>-1</sup> | kg   | M: laser cutting                                       | M: laser cutting                                                  |          |

Table 20: LCI data for laser cutting as part of the MLI foil material and manufacturing stage

| amount                | unit | product/biosphere flow      | activity/compartments                                | location |
|-----------------------|------|-----------------------------|------------------------------------------------------|----------|
| 1.00                  | kg   | M: laser cutting            | M: laser cutting                                     | GLO      |
| 1.93                  | kWh  | electricity, medium voltage | market group for electricity, medium voltage         | GLO      |
| 7.33*10 <sup>-3</sup> | kg   | activated carbon, granular  | activated carbon production, granular from hard coal | GLO      |
| 1.33*10 <sup>-3</sup> | kg   | glass fibre                 | market for glass fibre                               | GLO      |
| 3.33*10 <sup>-4</sup> | kg   | steel, low-alloyed          | market for steel, low-alloyed                        | GLO      |

Table 21: LCI data for weaving as part of the MLI foil material and manufacturing stage

| amount                 | unit | product/biosphere flow                                | activity/compartments                                           | location |
|------------------------|------|-------------------------------------------------------|-----------------------------------------------------------------|----------|
| 1.00                   | kg   | M: MLI weaving of synthetic fibre, for industrial use | M: MLI weaving of synthetic fibre, for industrial use           | GLO      |
| 3.94*10 <sup>-10</sup> | kg   | chemical factory, organics                            | market for chemical factory, organics                           | GLO      |
| 7.33*10 <sup>-1</sup>  | kWh  | electricity, high voltage                             | market group for electricity, high voltage                      | GLO      |
| -1.48*10 <sup>-2</sup> | kg   | waste polyester, industrial, from textile production  | market for waste polyester, industrial, from textile production | GLO      |

## Transportation stage

The assumptions employed in the modelling of the NICOLHy VIP also apply to the conventional insulation materials. For further details, please refer to Section 2.4.2.

## End-of-life stage

The same generic modelling assumptions as stated in Subsection 2.4.1 for the end-of-life stage modelling apply to the conventional VIP. In contrast to the VIPs, no preliminary treatment of the material in a sorting and separation step is modelled, as the assumption is made that the insulation materials are subject to direct treatment following the dismantling of the tank.

The management of polystyrene foam waste typically involves incineration [49]. The treatment of the MLI foil is approximated with an activity from [29] for the treatment of waste polyethylene terephthalate, which is in line with the treatment of its main constituents. It comprises the treatment pathways of incineration and landfill. It is assumed that a proportion of the aluminium present in the MLI foil is recovered after incineration, with a rate of 9% [45]. Details of the inventory modelling can be found in Table 22.

Table 22: LCI data of the insulation materials end-of-life stage

| amount | unit | product/biosphere flow                 | activity/compartments                  | location |
|--------|------|----------------------------------------|----------------------------------------|----------|
| -1.00  | kg   | expanded polystyrene to incineration   | expanded polystyrene to incineration   |          |
| -1.00  | kg   | waste expanded polystyrene             | market for waste expanded polystyrene  | CH       |
| -1.00  | kg   | MLI to landfill/incineration/recycling | MLI to landfill/incineration/recycling |          |

|                        |    |                                  |                                                          |     |
|------------------------|----|----------------------------------|----------------------------------------------------------|-----|
| -1.00                  | kg | waste polyethylene terephthalate | market group for waste polyethylene terephthalate        | RER |
| -7.90*10 <sup>-3</sup> | kg | aluminium scrap, post-consumer   | aluminium scrap, post-consumer, Recycled Content cut-off | GLO |

## 2.5 Life cycle impact assessment

Life cycle impact assessment involves the calculation of potential environmental impacts based on the collected LCI data. The collected data is used to model the environmental impact utilising the Activity Browser software [31]. In the software, the impact assessment method is selected, which in this study is the Environmental Footprint (EF) v. 3.1 method. The EF method is maintained by the European Commission and updated on a regular basis, with the most recent update being made in 2021 [50]. It covers 16 midpoint indicators [50], all of which are employed in the present study (see Table 23). The Midpoint indicators are based on groups of substance flows, that contribute to the same environmental effect [12]. The selection of the impact assessment method and indicators is followed by the choice of the activities for which the LCIA is to be executed. The reference flows are then quantified, and the calculation is executed. The results of the LCIA are copied and transferred to Excel for further analysis.

Table 23: Impact categories of the EF v 3.1 method [50]

| EF impact category                          | Impact category indicator                                           | Unit                                      |
|---------------------------------------------|---------------------------------------------------------------------|-------------------------------------------|
| Climate change, total                       | Global warming potential (GWP100)                                   | kg CO <sub>2</sub> eq                     |
| Ozone depletion                             | Ozone depletion potential (ODP)                                     | kg CFC-11 eq                              |
| Human toxicity, cancer                      | Comparative toxic unit for humans (CTU <sub>h</sub> )               | CTUh                                      |
| Human toxicity, non-cancer                  | Comparative toxic unit for humans (CTU <sub>h</sub> )               | CTUh                                      |
| Particulate matter                          | Impact on human health                                              | Disease incidence                         |
| Ionizing radiation, human health            | Human exposure efficiency relative to U <sup>235</sup>              | kBq U <sup>235</sup> eq                   |
| Photochemical ozone formation, human health | Tropospheric ozone concentration increase                           | kg NMVOC eq                               |
| Acidification                               | Accumulated exceedance (AE)                                         | mol H <sup>+</sup> 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 <sub>e</sub> )           | CTU <sub>e</sub>                          |
| Land use                                    | Soil quality index                                                  | Dimensionless                             |
| Water use                                   | User deprivation potential (deprivation weighted water consumption) | m <sup>3</sup> 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                                        |

## 2.6 Sensitivity analysis

Following the life cycle impact assessment of the VIP core materials, the VIPs, and the conventional insulation materials, a sensitivity analysis involving several scenarios is performed. The analysis focuses exclusively on the NICOLHy VIP concept, in line with the primary objective of this deliverable. With the first scenario, the sensitivity of the potential

environmental impacts of the core material, glass bubbles, is investigated. With the second, the sensitivity of the envelope material, steel foil, is studied.

- Scenario 1 (Sc. 1): Changing the European heat mix from natural gas to
  - Sc. 1.1: Wood-chips based renewable heat (Germany)
  - Sc. 1.2: Hard coal-based heat (European)
- Scenario (Sc.) 2: Changing the German electricity grid mix to
  - Sc. 2.1: Wind, 1-3 MW turbine, onshore (Germany)
  - Sc. 2.2: Hard coal-based electricity (Germany)
- Scenario 3 (Sc. 3): Manufacturing of the steel foil using the following ratios of recycled steel:
  - Sc. 3.1: 25% recycled steel
  - Sc. 3.2: 50% recycled steel
  - Sc. 3.3: 75% recycled steel

With the first two scenarios, the effects of renewable vs. non-renewable energy sources are investigated. The second scenario enables the study of the effect of using recycled steel in the manufacture of the steel foil. In fact, the global percentage of recycled iron input to steel-making amounts to ~30% on a global level [51].

## 2.7 Uncertainty quantification

The uncertainty of the collected LCI data is semi-quantitatively assessed employing the pedigree-matrix approach. It covers basic uncertainty due to variation and stochastic error and additional uncertainty influenced by the quality of the data collected for the LCI. The first aspect is ideally quantified employing statistical methods. However, here the simplified approach via assuming a log-normal distribution is followed. Additional uncertainty is addressed by the five data quality indicators and their respective five indicator scores [12] namely: reliability (sampling methods and verification procedures), completeness (statistical representativeness), temporal-, geographical-, and further technological correlation (for data deviating from its actual context) [52]. The pedigree matrix is shown in Figure 6.

|                                          |                                                                                                                                   |                                                                                                                                            |                                                                                                                                   |                                                                                                                     |                                                                                                                         |
|------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| <b>Reliability</b>                       | 1: Verified data based on measurements                                                                                            | 2: Verified data partly based on assumptions or non-verified data based on measurements                                                    | 3: Non-verified data partly based on qualified estimates                                                                          | 4: Qualified estimate (e.g. by industrial expert)                                                                   | 5: Non-qualified estimate                                                                                               |
| <b>Completeness</b>                      | 1: Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations | 2: Representative data from >50 % of the sites relevant for the market considered, over an adequate period to even out normal fluctuations | 3: Representative data from only some sites (<50 %) relevant for the market considered or >50 % of sites but from shorter periods | 4: Representative data from only one site relevant for the market considered or some sites but from shorter periods | 5: Representativeness unknown or data from a small number of sites and from shorter periods                             |
| <b>Temporal correlation</b>              | 1: Less than 3 years of difference to the time period of the dataset                                                              | 2: Less than 6 years of difference to the time period of the dataset                                                                       | 3: Less than 10 years of difference to the time period of the dataset                                                             | 4: Less than 15 years of difference to the time period of the dataset                                               | 5: Age of data unknown or more than 15 years of difference to the time period of the dataset                            |
| <b>Geographical correlation</b>          | 1: Data from area under study                                                                                                     | 2: Average data from larger area in which the area under study is included                                                                 | 3: Data from area with similar production conditions                                                                              | 4: Data from area with slightly similar production conditions                                                       | 5: Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) |
| <b>Further technological correlation</b> | 1: Data from enterprises, processes and materials under study                                                                     | 2: Data from processes and materials under study (i.e. identical technology) but from different enterprises                                | 3: Data from processes and materials under study from different technology                                                        | 4: Data on related processes or materials                                                                           | 5: Data on related processes on laboratory scale or from different technology                                           |

Figure 6: Pedigree matrix for semi-quantitative assignment of uncertainties

Each indicator score is associated with an uncertainty factor (e.g. 1.69 corresponds to a *reliability* score of 4), which were initially based on expert judgements and updated employing empirical data in 2016. These uncertainty factors are aggregated into a standard deviation of the here assumed log-normal distribution [12]. The assigned uncertainty information of the LCI datasets allows to propagate a cumulative uncertainty with a Monte Carlo simulation. The result is a probability distribution for each assessed impact category, instead of a single indicator score.

The undertaken uncertainty analysis focuses exclusively on the VIP life cycles. Furthermore, the uncertainty of the other VIP components (such as opacifier, sensor, etc., compare Subsection 2.4.2, Table 11) is excluded, as these are identical in both VIPs under study. Hence, following life cycle stages with their respective processes are covered:

- NICOLHy VIP:
  - Raw material extraction and manufacturing of:
    - Glass bubbles
    - Steel foil
  - Manufacturing of the VIP
  - EoL stage of:
    - VIP sorting and separation
    - Glass bubbles
    - Steel foil
- Conventional VIP:
  - Raw material extraction and manufacturing of:
    - Fumed silica
    - Trilaminate foil
  - Manufacturing of the VIP
  - EoL stage of:
    - VIP sorting and separation
    - Fumed silica
    - Trilaminate foil

Using the pedigree matrix, the input uncertainties are assigned to each of the above-listed processes. This is done for each process individually, considering its inputs and outputs and their respective data quality. For instance, fumed silica is modelled using data from [36], which is a Best Available Technique Reference document from 2007. This results in each input to the fumed silica process being assigned a temporal correlation score of 5, given that the age of the data is older than 15 years. For activities that are modelled by replicating or modifying an ecoinvent activity, the predefined uncertainties of the dataset are used.

The resulting input uncertainties for each LCI are shown in Table 24 – Table 33, starting with the NICOLHy VIP data, followed by the data for the conventional VIP, beginning from Table 30.

Table 24: Uncertainty data for glass bubbles

| product/biosphere flow                               | activity/compartments                                           | location                   | pedigree <sup>d</sup> |
|------------------------------------------------------|-----------------------------------------------------------------|----------------------------|-----------------------|
| glass bubbles                                        | glass bubbles production                                        |                            |                       |
| boric oxide                                          | market for boric oxide                                          | GLO                        | 3,3,4,3,1             |
| silica sand                                          | market for silica sand                                          | GLO                        | 3,3,4,3,1             |
| soda ash, light                                      | market for soda ash, light                                      | RER                        | 3,3,4,3,1             |
| limestone, milled, packed                            | market for limestone, milled, packed                            | Europe without Switzerland | 3,3,4,3,1             |
| sodium sulfate, anhydrite                            | market for sodium sulfate, anhydrite                            | RoW                        | 3,5,4,5,4             |
| electricity, medium voltage                          | market for electricity, medium voltage                          | DE                         | 2,2,5,3,1             |
| heat, district or industrial, natural gas            | market for heat, district or industrial, natural gas            | Europe without Switzerland | 2,2,5,3,1             |
| heat, district or industrial, other than natural gas | market for heat, district or industrial, other than natural gas | Europe without Switzerland | 2,2,5,3,1             |

Table 25: Uncertainty data for steel foil

| product/biosphere flow                 | activity/compartments                             | location | pedigree <sup>d</sup> |
|----------------------------------------|---------------------------------------------------|----------|-----------------------|
| steel foil envelope                    | steel foil production                             |          |                       |
| steel, chromium steel 18/8, hot rolled | market for steel, chromium steel 18/8, hot rolled | GLO      | 3,2,1,2,3             |
| sheet rolling, chromium steel          | market for sheet rolling, chromium steel          | GLO      | 4,5,1,2,5             |

Table 26: Uncertainty data for manufacturing the VIP

| product/biosphere flow      | activity/compartments                        | location                   | pedigree <sup>d</sup> |
|-----------------------------|----------------------------------------------|----------------------------|-----------------------|
| NICOLHy VIP                 | VIP assembly                                 |                            |                       |
| electricity, medium voltage | market group for electricity, medium voltage | Europe without Switzerland | 3,4,2,2,5             |
| building machine            | building machine production                  | RER                        | 4,5,1,2,5             |

Table 27: Uncertainty data for dismantling the VIP

| product/biosphere flow                         | activity/compartments                     | location | pedigree <sup>d</sup> |
|------------------------------------------------|-------------------------------------------|----------|-----------------------|
| VIP components for further treatment/recycling | VIP disassembly                           |          |                       |
| electricity, low voltage                       | market group for electricity, low voltage | CH       | 1,1,5,1,1             |
| excavation, hydraulic digger                   | excavation, hydraulic digger              | RER      | 1,1,5,1,1             |
| sorting facility for construction waste        | sorting facility for construction waste   | CH       | 1,1,5,1,1             |

Table 28: Uncertainty data for the glass bubbles end-of-life stage

| product/biosphere flow | activity/compartments                          | location | pedigree <sup>d</sup> |
|------------------------|------------------------------------------------|----------|-----------------------|
| glass for recycling    | glass for recycling                            |          |                       |
| glass cullet, sorted   | glass cullet, sorted, Recycled Content cut-off | GLO      | 4,5,1,1,4             |

Table 29: Uncertainty data for the end-of-life stage of steel foil

| product/biosphere flow          | activity/compartments | location | pedigree <sup>d</sup> |
|---------------------------------|-----------------------|----------|-----------------------|
| steel for recycling             | steel for recycling   |          |                       |
| market for iron scrap, unsorted | iron scrap, unsorted  | GLO      | 4,5,1,2,4             |

The following tables, Table 30 – Table 31, show the uncertainty data for the conventional VIP. The uncertainty data for manufacturing the VIP and the disassembly of the VIP are identical for both the NICOLHy and the conventional VIP.

Table 30: Uncertainty data for pyrogenic silica material and manufacturing data

| product/biosphere flow            | activity/compartments                        | location                   | pedigree <sup>d</sup> |
|-----------------------------------|----------------------------------------------|----------------------------|-----------------------|
| pyrogenic silica                  | pyrogenic silica production                  |                            |                       |
| hydrogen, gaseous, low pressure   | hydrogen production, steam methane reforming | RER                        | 3,1,5,1,1             |
| silicon tetrachloride             | market for silicon tetrachloride             | RoW                        | 3,1,5,3,1             |
| inert waste, for final disposal   | market for inert waste, for final disposal   | CH                         | 3,1,5,3,1             |
| electricity, medium voltage       | market group for electricity, medium voltage | Europe without Switzerland | 3,1,5,1,1             |
| hazardous waste, for incineration | market for hazardous waste, for incineration | Europe without Switzerland | 3,1,5,1,1             |
| carbon dioxide, fossil            | air                                          |                            | 3,1,5,1,1             |
| chlorine                          | air                                          |                            | 3,1,5,1,1             |
| hydrochloric acid                 | air                                          |                            | 3,1,5,1,1             |
| chemical factory, organics        | chemical factory construction, organics      | RER                        | 4,5,1,1,5             |

Table 31: Uncertainty data for the trilaminate foil materials and manufacturing stage

| product/biosphere flow                   | activity/compartments                               | location                   | pedigree <sup>d</sup> |
|------------------------------------------|-----------------------------------------------------|----------------------------|-----------------------|
| trilaminate foil envelope                | trilaminate foil production                         |                            |                       |
| methyl ethyl ketone                      | market for methyl ethyl ketone                      | RER                        | 1, 4, 2, 1, 2         |
| methylene diphenyl diisocyanate          | market for methylene diphenyl diisocyanate          | RER                        | 2, 4, 2, 1, 2         |
| packaging film, low-density polyethylene | market for packaging film, low-density polyethylene | GLO                        | 2, 4, 2, 2, 3         |
| polyol                                   | market for polyol                                   | RER                        | 2, 4, 2, 1, 2         |
| electricity, medium voltage              | market group for electricity, medium voltage        | Europe without Switzerland | 1, 4, 2, 1, 1         |
| sheet rolling, aluminium                 | sheet rolling, aluminium                            | RER                        | 2, 4, 1, 1, 4         |

|                          |                                     |     |               |
|--------------------------|-------------------------------------|-----|---------------|
| aluminium, wrought alloy | market for aluminium, wrought alloy | GLO | 2, 4, 2, 2, 2 |
|--------------------------|-------------------------------------|-----|---------------|

Table 32: Uncertainty data of the insulation materials end-of-life stage

| product/biosphere flow     | activity/compartments                            | location | pedigree <sup>d</sup> |
|----------------------------|--------------------------------------------------|----------|-----------------------|
| fumed silica for recycling | fumed silica for recycling                       |          |                       |
| silica fume, densified     | silica fume, densified, Recycled Content cut-off | GLO      | 4,5,1,2,4             |

Table 33: Uncertainty data of the end-of-life stage of trilaminate foil

| product/biosphere flow                                   | activity/compartments          | location | pedigree <sup>d</sup> |
|----------------------------------------------------------|--------------------------------|----------|-----------------------|
| trilaminate                                              | trilaminate                    |          |                       |
| market group for waste plastic, mixture                  | waste plastic, mixture         | RER      | 5,5,1,2,4             |
| aluminium scrap, post-consumer, Recycled Content cut-off | aluminium scrap, post-consumer | GLO      | 4,5,1,1,4             |

<sup>d</sup> pedigree: (reliability, completeness, temporal-, geographical-, further technological correlation)

The resulting probability distributions can be found in Section 3.6.

## 2.8 Assumptions

This section details the assumptions made in the present study.

The functional unit is predicated on the assumption that the compared product systems are able to fulfil the same function. In the current study, it is assumed that the thermal performance of the insulation materials is equal, which is fulfilled by the according reference flows. This includes the assumption of an identical lifetime. Moreover, it is presumed that the configuration of the tank comprises an inner and an outer tank, with the insulation situated between these components.

It is further assumed that the processes modelled in the life cycle inventory are sufficiently representative for the purposes of the present study. This assumption is required to be able to benchmark the investigated insulation materials / concepts. It should be noted, however, that the quality of the LCI data used differs. Hence, the uncertainty study (see Section 2.7 and Section 3.6) is conducted of the insulation concept of primary subject, which is the two VIPs.

In relation to the other components of a VIP, i.e. the components other than the core and the envelope, it is assumed, that the materials selected from [7] are a viable option for the NICOLHy concept.

In the context of the EoL stage, it is anticipated, that the VIP will undergo a sorting and separation procedure. However, alternative treatment options may involve incineration or landfill, which would result in the core and the envelope material not being recycled. It is further assumed that the rate of recycling of glass bubbles is 100%, which relates to an ideal scenario.

Another assumption made in relation to the analysis of the results concerns the differentiation of the material and the manufacturing stage. In the context of the manufacturing stage, only the manufacturing of components of the foreground system are covered. In the material stage, the extraction of raw materials and any upstream processes that are necessary to supply the raw materials and pre-products that are required for the manufacture of the insulation material/concept's component in question are included.

### 3 Results and Analysis

The following subsections present the results of the LCA of the NICOLHy concept, the conventional VIPs, and the conventional insulation materials. In addition, a benchmarking analysis is presented, followed by the results of the sensitivity study.

#### 3.1 VIP core materials

As presented in Subsection 2.3.1, the core materials studied are glass fibre, silica aerogel, glass bubbles, expanded perlite, polyurethane foam, and fumed silica. The potential environmental impacts are shown in Figure 7 as normalized indicators relative to the maximum in each category. The sixteen impact categories are given similar importance, indicating that silica aerogel, followed by polyurethane foam, are the materials with the least environmental performance. Specifically, silica aerogel shows the highest environmental burden in 13 of the 16 impact categories investigated, while polyurethane foam ranks highest in the remaining 3 categories, making them the least environmentally favourable options.

The material with the most favourable environmental performance is expanded perlite, having the lowest potential environmental impact in 11 of the 16 categories. Glass bubbles have the lowest impact in the categories of water use, ozone depletion, and carcinogenic human toxicity, while glass fibre performs best in the categories of freshwater ecotoxicity, and land use.

The environmental performance of fumed silica is neither superior nor inferior to those of the other studied VIP core materials in any impact category. However, its performance surpasses those of certain materials in specific categories, for instance, expanded perlite in ozone depletion, and freshwater ecotoxicity. In addition, it showed better environmental performance over glass bubbles with respect to land use, metals/minerals resources, and marine and terrestrial eutrophication, as well as glass fibre in relation to non-carcinogenic human toxicity and metals/minerals resources.

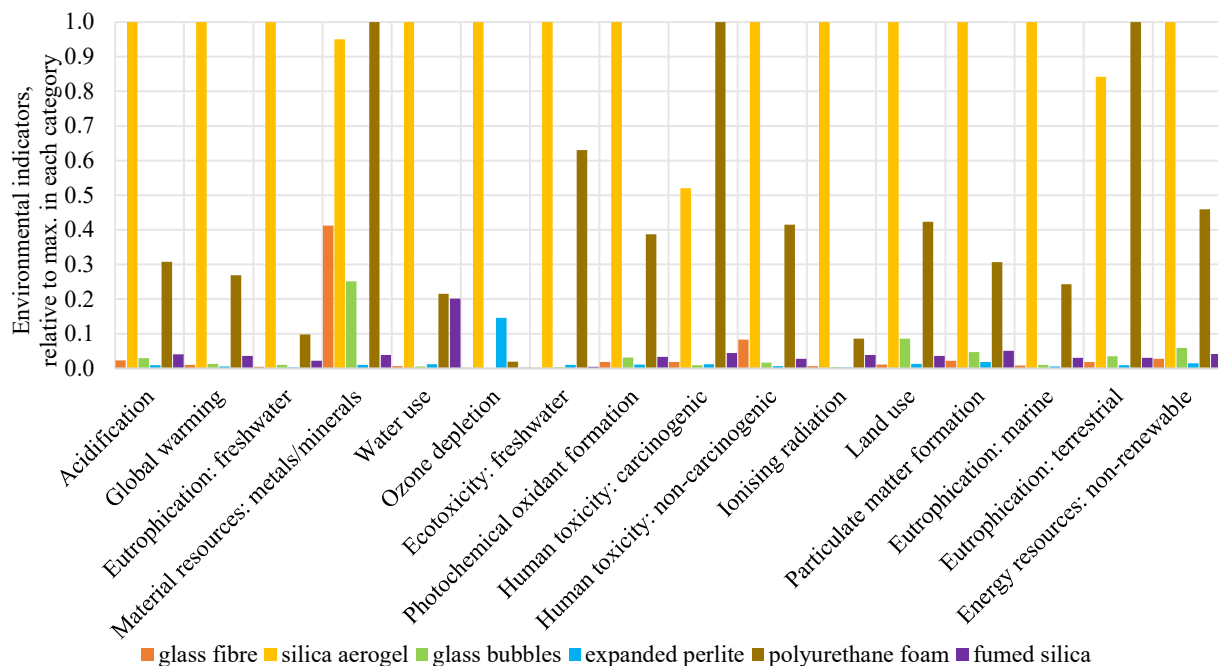


Figure 7: Life cycle impact assessment results from cradle-to-grave of the VIP core materials glass fibre, silica aerogel, glass bubbles, expanded perlite, polyurethane foam, and fumed silica as indicators relative to the maximum in each category, maximum set to 1 with the other values scaled accordingly

An in-depth analysis (refer to Figure 8) is carried out, excluding silica aerogel and polyurethane foam due to their poor environmental performance. The analysis focuses on six impact categories, with particular attention to the different life cycle stages. Five of the six impact categories are chosen based on those showing the greatest variation in score among the materials covered in the benchmarking study (see Subsection 3.4), which includes all materials investigated in this deliverable. In addition, climate change is included as an impact category because of its significant societal relevance.

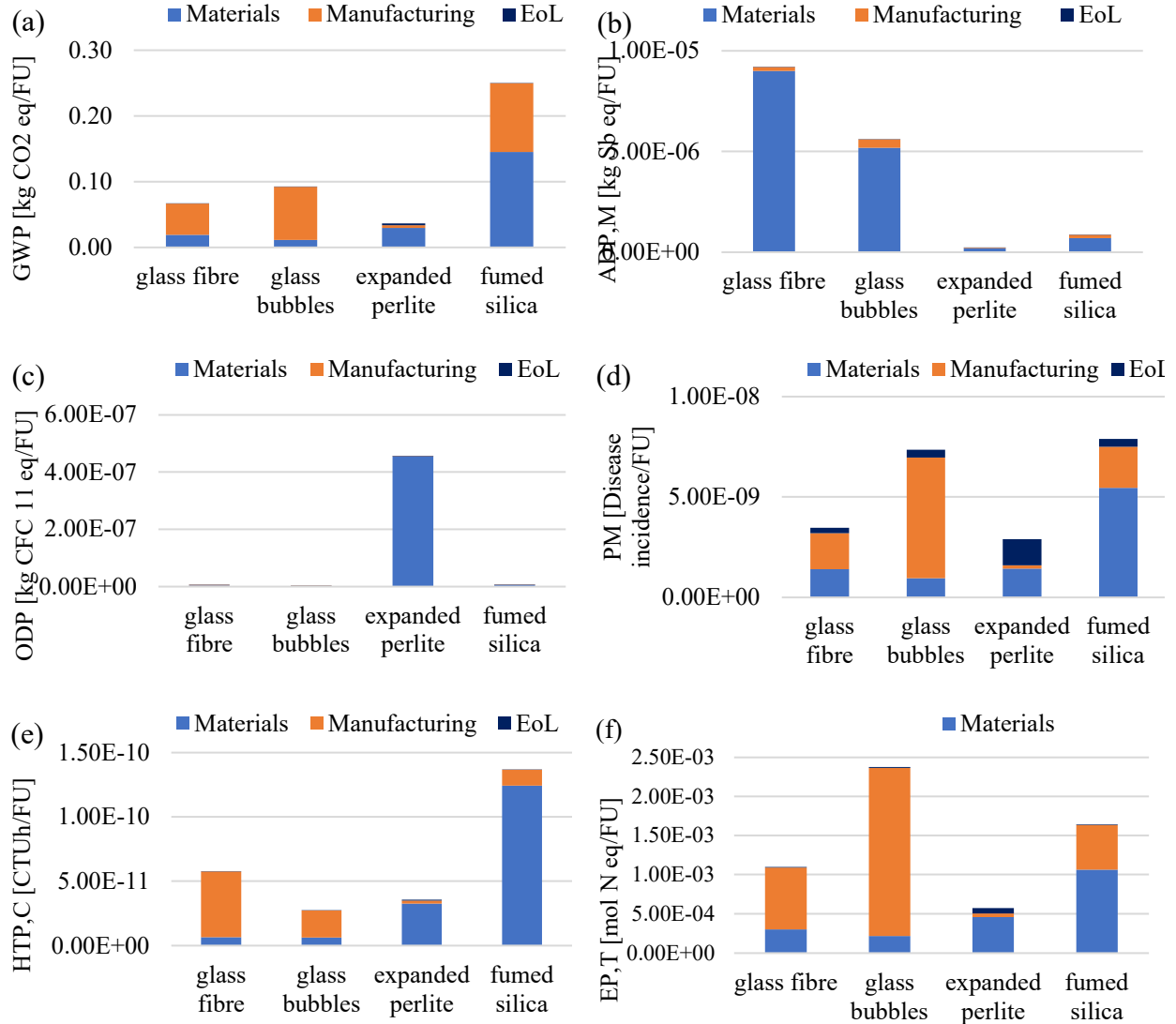


Figure 8: Environmental impacts of selected VIP core materials and impact categories per functional unit; “Materials” relates to the (raw) material stage, “Manufacturing” relates to the manufacturing stage, and “EoL” to the end-of-life stage; (a): Global warming potential, (b): Material resources: metals/minerals; (c): Ozone depletion potential, (d): Particulate matter formation; (e) Human toxicity, cancer; (f) Eutrophication, terrestrial

From Figure 8, it can be seen that the manufacturing stage contributes the highest to the environmental impact of the glass-based materials in majority of the categories. In fact, in five of the six impact categories, the manufacturing stage is dominant in the case of glass bubbles, with the exception being material resources: metals/minerals. With regard to glass fibre, this is the case for four impact categories, except for ozone depletion and material resources: metals/minerals. In the case of expanded perlite, the raw material extraction stage plays a particularly important role, a trend similarly observed for fumed silica across all impact categories. The end-of-life stage generally has a negligible environmental impact for all studied

materials, with the exception of expanded perlite, where it substantially affects particulate matter formation.

### 3.2 NICOLHy concept

The NICOLHy concept involves a VIP composed of a glass bubble core and a steel foil envelope. Additionally, other VIP components, such as opacifier and sensor, are incorporated within the LCI, as presented in Subsection 2.4.2.

The potential environmental impacts of the NICOLHy concept are studied for the six chosen impact categories as introduced in Subsection 3.1. As illustrated in Figure 9 and Figure 10, the analysis is conducted on two distinct levels: low-resolution (on the left-hand side) and high-resolution (on the right-hand side).

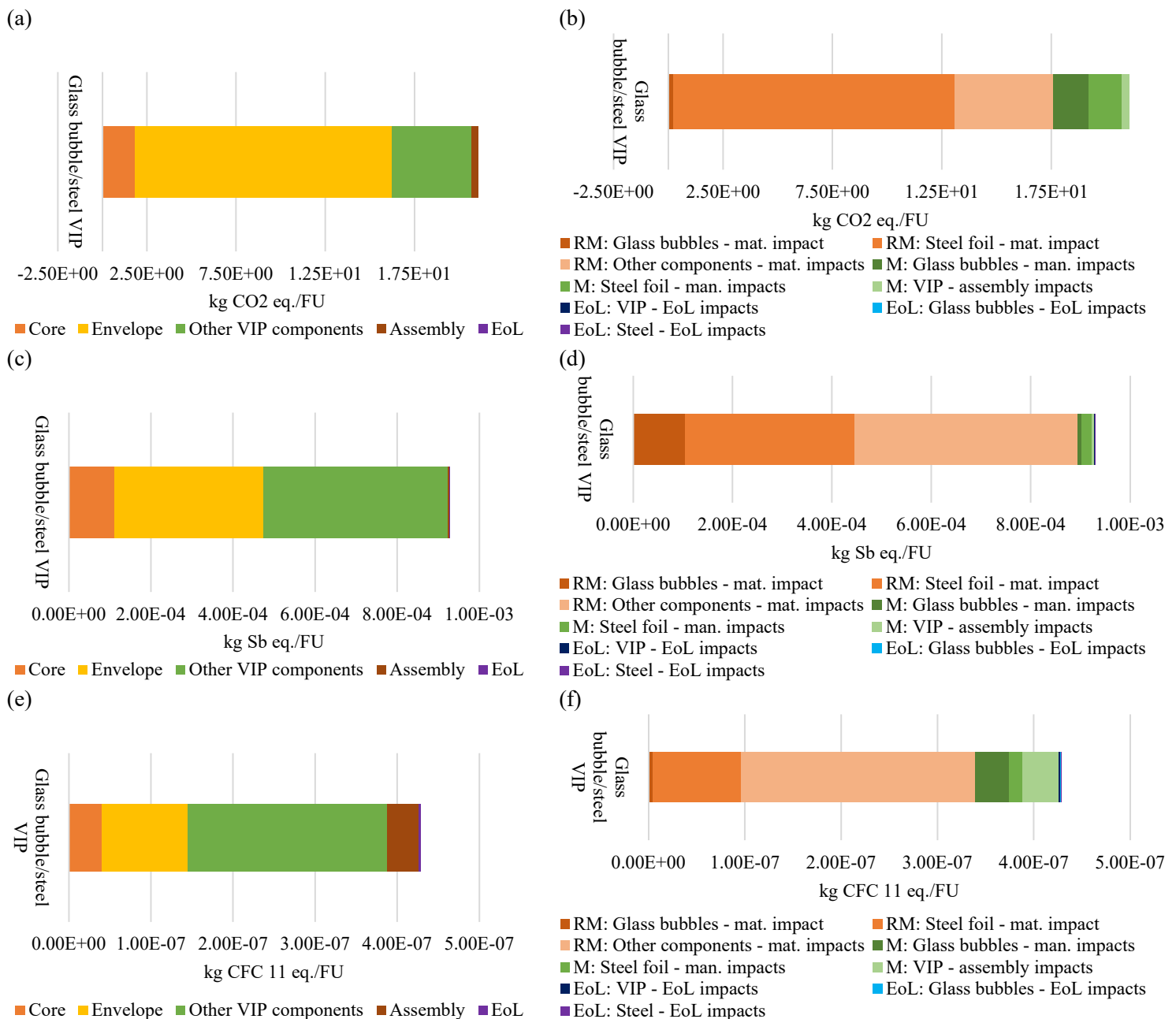


Figure 9: Environmental impacts of the NICOLHy VIP of selected impact categories with a low-resolution breakdown of core material-, envelope-, other VIP component-, assembly-, and EoL-impact ((a), (c), (e)) and a high-resolution breakdown including life cycle stage details ((b), (d), (f)). (a), (b): Global warming potential; (c), (d) Material resources: metals/minerals; (e), (f): Ozone depletion potential

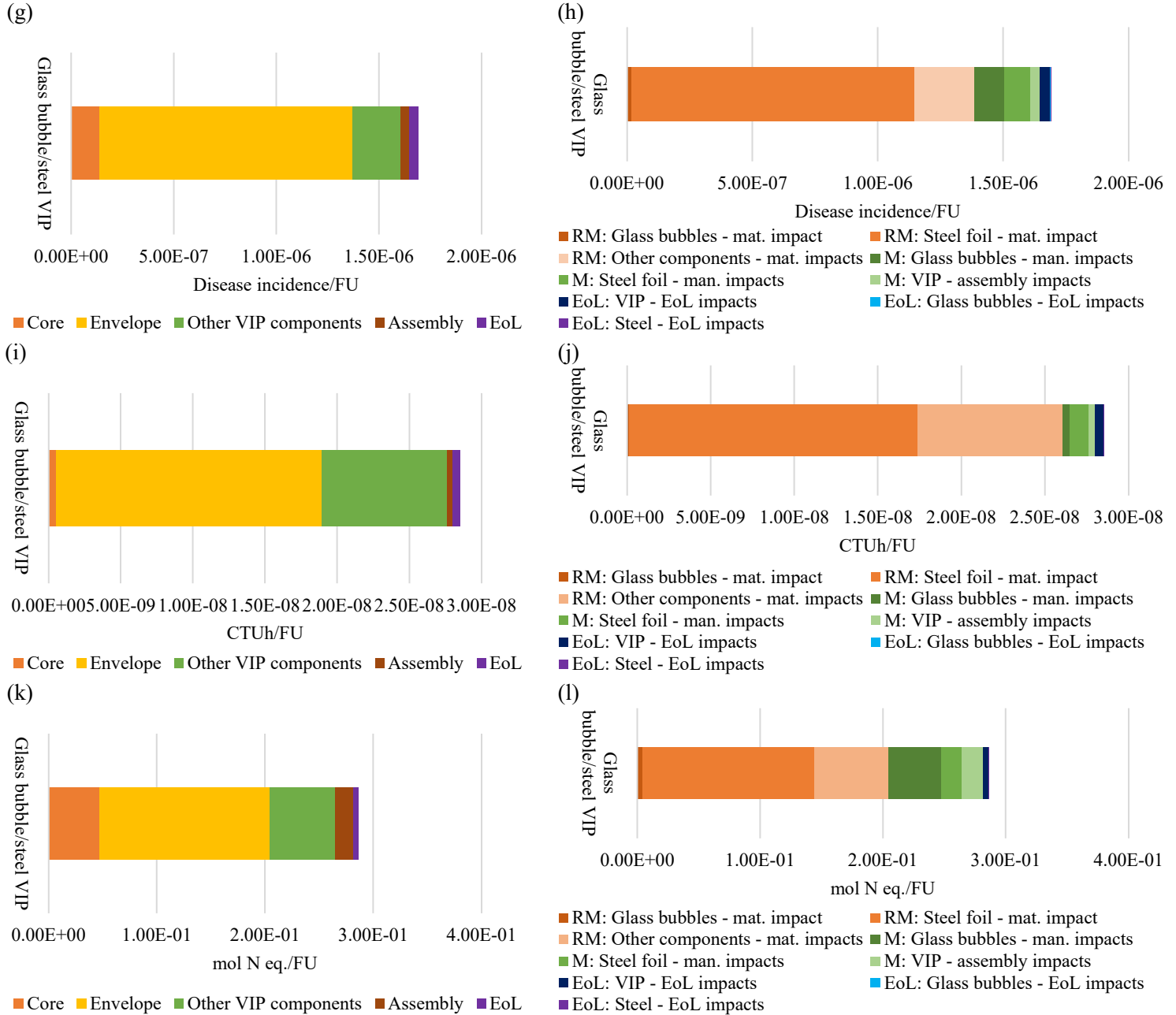


Figure 10: Environmental impacts of the NICOLHy VIP of selected impact categories with a low-resolution breakdown of core material-, envelope-, other VIP component-, assembly-, and EoL-impact ((g), (i), (k)) and a high-resolution breakdown including life cycle stage details ((h), (j), (l)). (g), (h): Particulate matter formation; (i), (j): Human toxicity: cancer; (k), (l): Eutrophication: terrestrial

From the results on a low-resolution level, it is evident that the envelope contributes significantly to the potential environmental impact of the VIP. It is the main contributor in four of the six analysed impact categories. In the categories, material resources: metals/minerals, and ozone depletion, the other VIP components pose the most significant impacts. The results on the right-hand side indicate that the primary contributor to the environmental impacts is the raw material extraction of the steel foil. It should be noted, however, that it includes all upstream activities to result in a steel suitable for further processing into foil. Analogous observations and assertions can be made with regard to the other VIP components.

For the end-of-life stage, the findings show only minor contributions to the total environmental impact of the VIP in the analysed impact categories.

### 3.3 Conventional insulation material

The following materials were studied as conventional insulation materials: expanded perlite, polyurethane foam, MLI, silica aerogel, glass fibre, and polystyrene foam. Their potential environmental impacts are presented in Figure 11 as normalized indicators relative to the maximum in each category. The results show that silica aerogel exhibits the highest environmental impacts across all sixteen studied impact categories.

Out of the sixteen impact categories assessed, EPS foam ranks as the most environmentally friendly option in twelve. Glass fibre performs best in the remaining four categories (climate change, water use, freshwater ecotoxicity, and non-renewable energy resources). However, glass fibre ranks as the second worst performing among all materials in the material resources: metals/minerals category. Silica aerogel shows the lowest environmental performance overall.

A comparison of the remaining three materials, namely expanded perlite, polyurethane foam, and MLI, reveals that MLI is the least environmentally friendly option. The results indicate that in eleven impact categories, MLI is outperformed by expanded perlite and polyurethane foam. This is followed by PUR foam, which is outperformed in four impact categories (material resources: metals/minerals, freshwater ecotoxicity, human toxicity, cancer, and marine eutrophication) by the other two materials. Expanded perlite performs best among these three, except in the ozone depletion category, where it ranks lower than the other two.

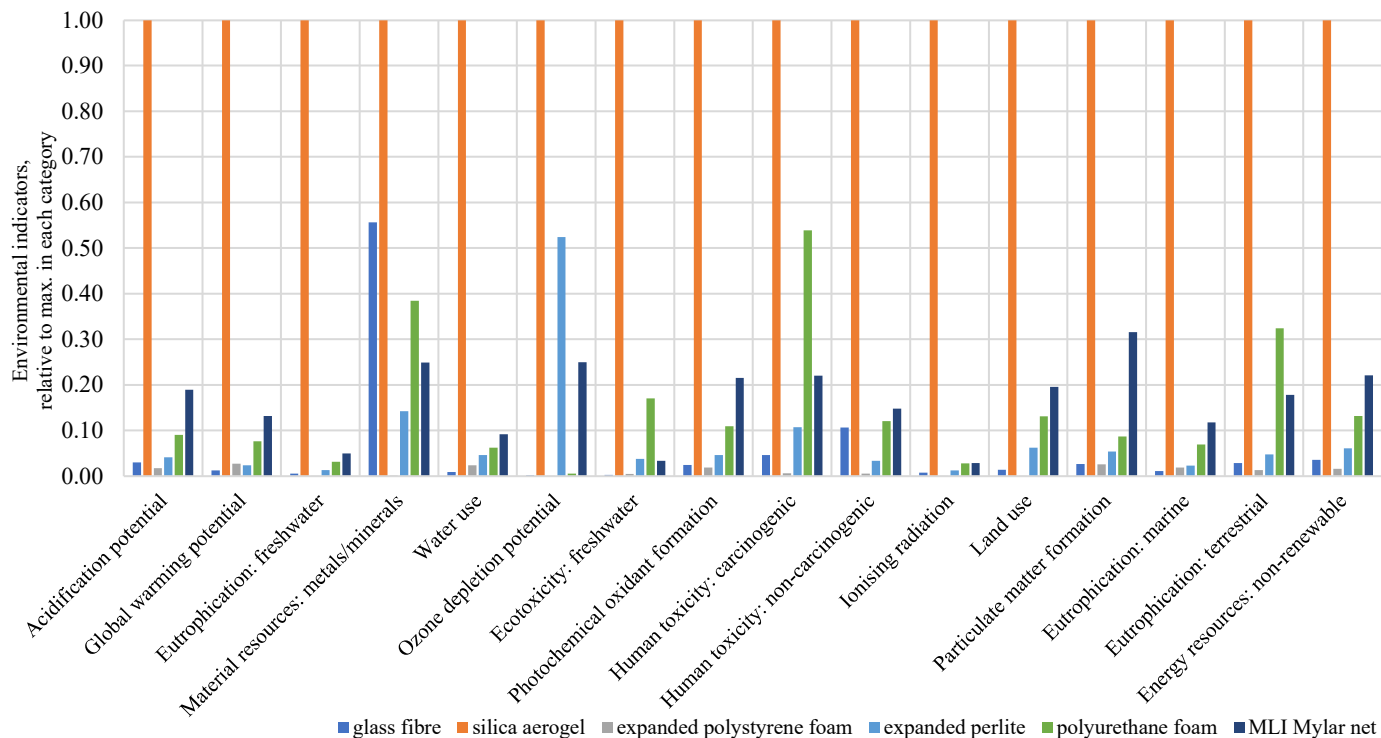


Figure 11: Life cycle impact assessment results from cradle-to-grave of the conventional insulation materials glass fibre, silica aerogel, expanded perlite, polyurethane foam, and MLI Mylar net as indicators relative to the maximum in each category, maximum set to 1 with the other values scaled accordingly

An in-depth analysis (see Figure 12) is conducted with the aid of the six impact categories chosen. The analysis is conducted on a life cycle stage basis. Silica aerogel is excluded due to its poor environmental performance.

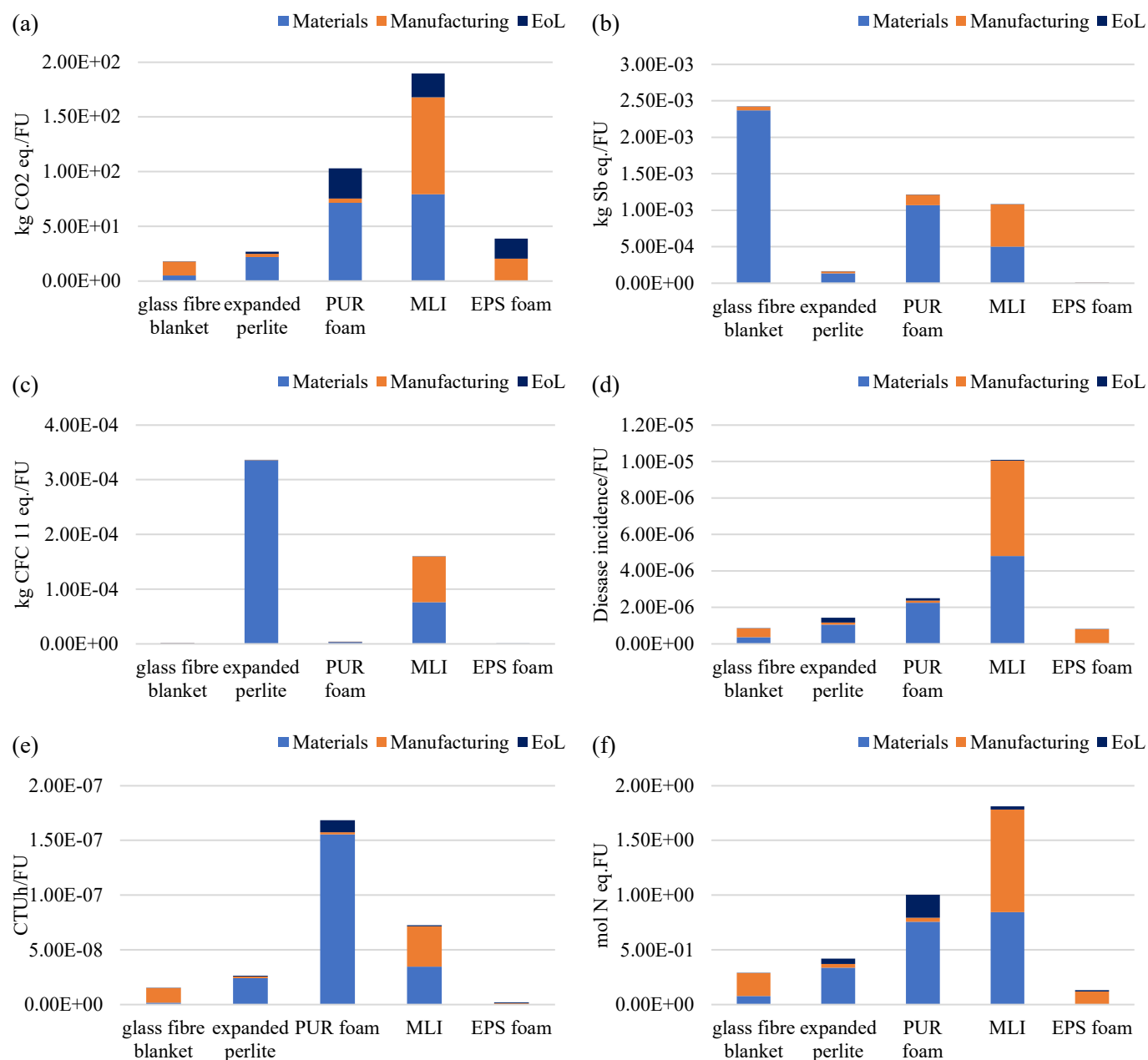


Figure 12: Environmental impacts of conventional insulation materials and impact categories per functional unit; “Materials” relates to the (raw) material stage, “Manufacturing” relates to the manufacturing stage, and “EoL” to the end-of-life stage; (a): Global warming potential, (b): Material resources: metals/minerals; (c): Ozone depletion potential, (d): Particulate matter formation; (e): human toxicity, cancer; (f): Eutrophication, terrestrial

There is a clear tendency for either the material stage or the manufacturing stage to be the primary contributor to environmental impacts. The insulation materials with the highest contribution from the raw material extraction stage are expanded perlite and polyurethane foam. This finding is observed for all six impact categories studied. It should be noted that this stage can contain impacts from upstream activities and therefore should not be considered exclusively as relating to the impacts of the raw materials themselves. For the other three

materials, glass fibre, MLI, and expanded polystyrene foam, the manufacturing stage is identified as the primary contributor to their environmental impacts. In the case of glass fibre, the material stage is the main contributor to the material resources: metals/minerals impact category, while the manufacturing stage is the primary contributor to the other investigated impact categories. In all six studied impact categories, the manufacturing stage of MLI and EPS foam is the most significant driver of their environmental impacts.

The end-of-life stage generally plays a minor role in the overall environmental impact across all materials and impact categories studied. However, it significantly contributes to climate change impacts for PUR, EPS foam, and MLI, accounting for 25.2%, 47.4%, and 11.5% of the total kg CO<sub>2</sub> eq./FU, respectively. Furthermore, the EoL stage has a notable impact on human toxicity (cancer) for PUR and EPS foam, with contributions of 6.2%, and 36.3%, respectively. It also affects terrestrial eutrophication, contributing 19.3% for and 8.9% for EPS foam.

### 3.4 Benchmarking analysis

The NICOLHy VIP is benchmarked against a conventional VIP and against conventional insulation materials. These analyses are presented in the following subsections.

#### 3.4.1 NICOLHy VIP and conventional VIP

The following analysis benchmarks the NICOLHy VIP to the conventional VIP. Their potential environmental impacts are presented in Figure 13 as normalized indicators relative to the maximum in each category. It has to be noted that the analysis is conducted disregarding the impacts of the other VIP components (sensor, opacifier, etc. compare Subsection 2.4.2, Table 11). This is done because the “other VIP components” are the same for both studied VIPs and thus have the same environmental impacts.

Each of the analysed impact categories is treated as being of equal importance. Therefore, the results in Figure 13 demonstrate that the conventional VIP outperforms the NICOLHy VIP in thirteen of sixteen impact categories. This reveals a superior environmental performance of the conventional VIP.

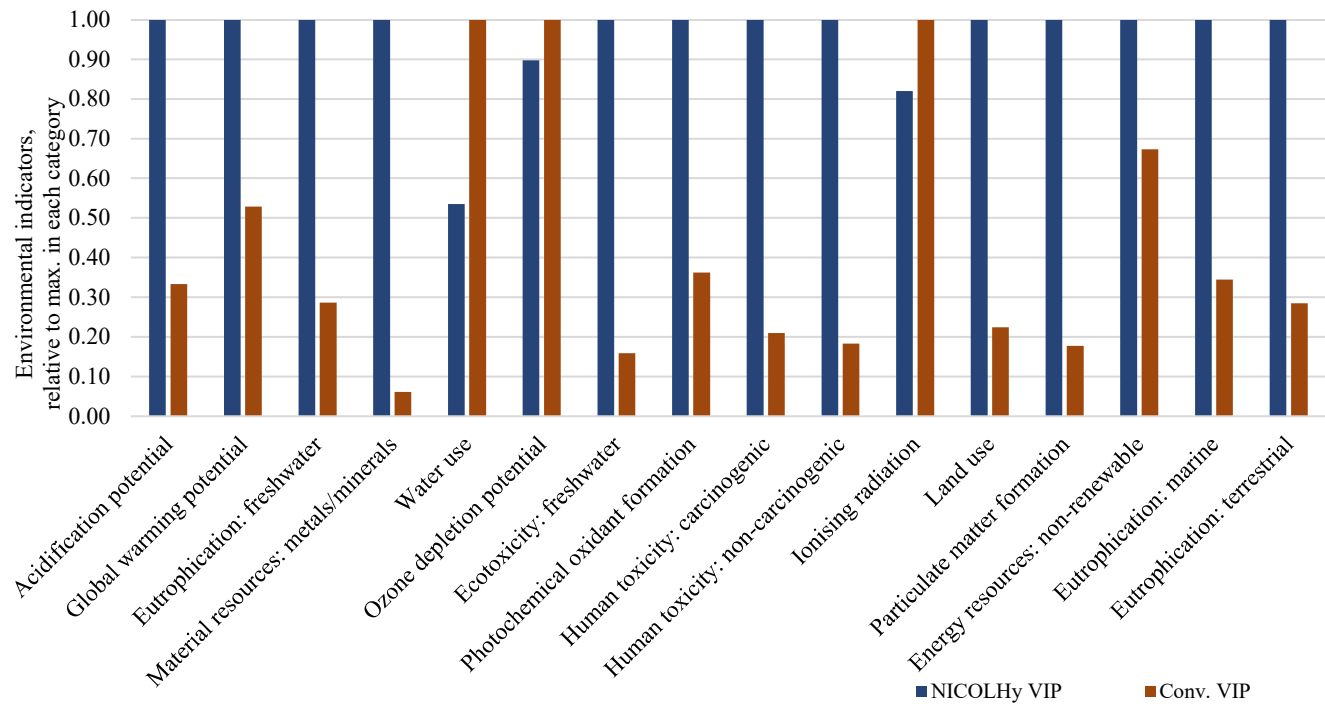
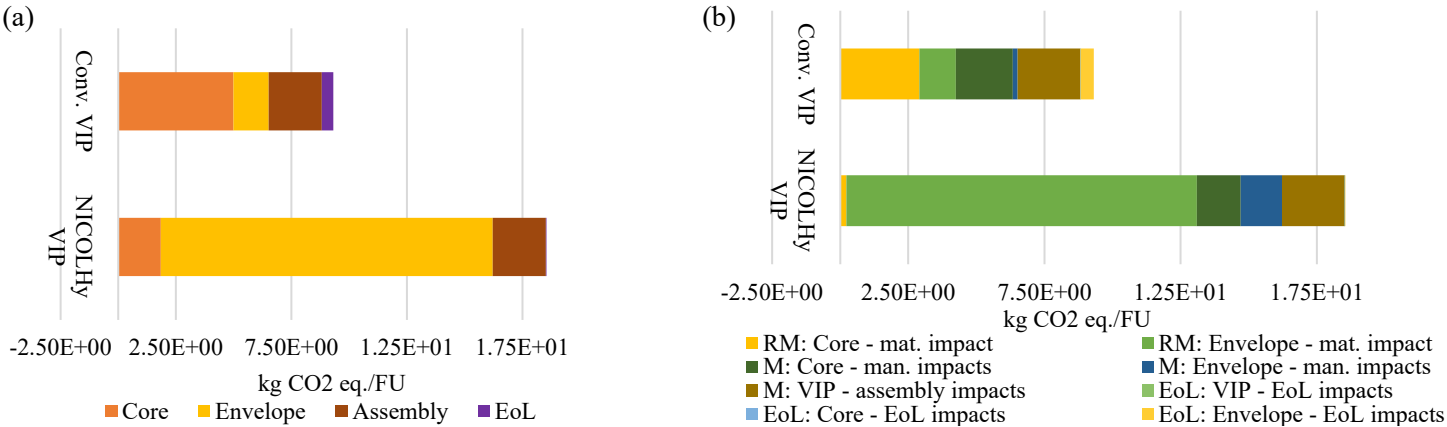


Figure 13: Life cycle impact assessment results from cradle-to-grave of the NICOLHy and the conventional VIP (Conv. VIP) as indicators relative to the maximum in each category, maximum set to 1 with the other values scaled accordingly

An in-depth analysis (see Figure 14 and Figure 15) is undertaken with the aid of the six impact categories selected. The analysis is conducted on a life cycle stage basis.



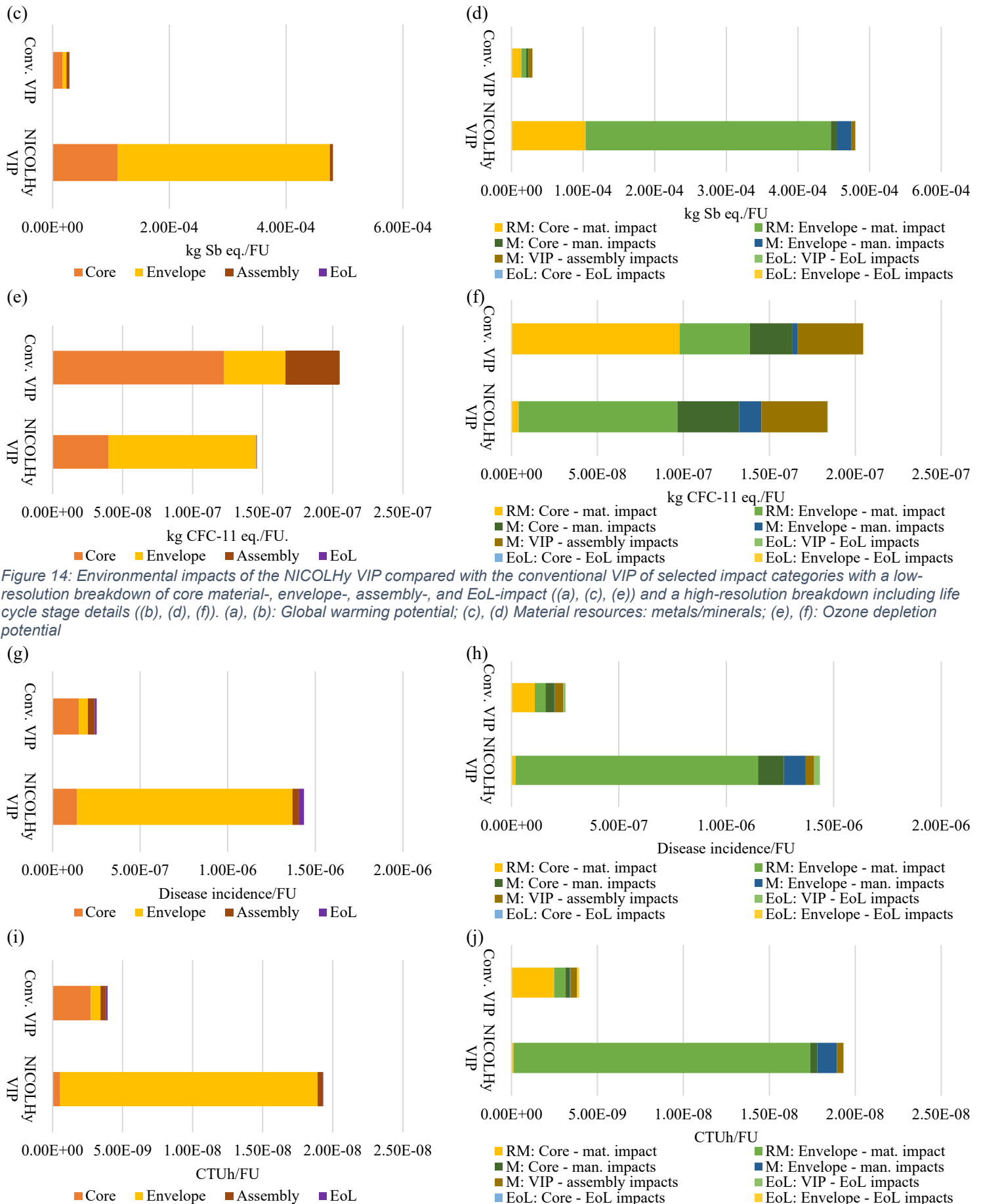


Figure 14: Environmental impacts of the NICOLHy VIP compared with the conventional VIP of selected impact categories with a low-resolution breakdown of core material-, envelope-, assembly-, and EoL-impact ((a), (c), (e)) and a high-resolution breakdown including life cycle stage details ((b), (d), (f)). (a), (b): Global warming potential; (c), (d) Material resources: metals/minerals; (e), (f): Ozone depletion potential

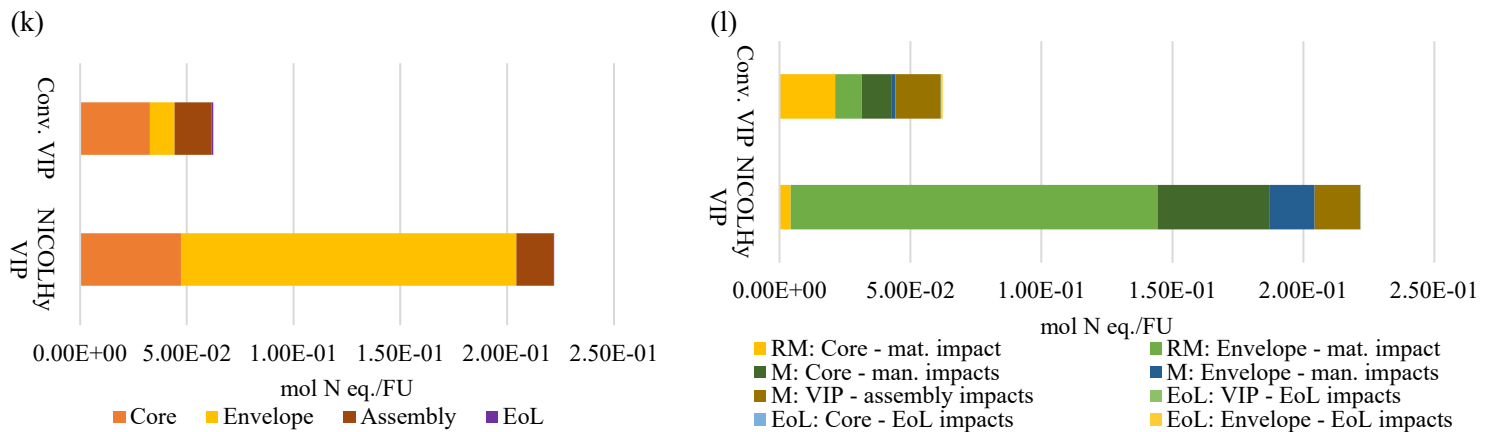


Figure 15: Environmental impacts of the NICOLHy VIP compared with the conventional VIP of selected impact categories with a low-resolution breakdown of core material-, envelope-, assembly-, and EoL-impact ((g), (i), (k)) and a high-resolution breakdown including life cycle stage details ((h), (j), (l)). (a), (b): (g), (h): Particulate matter formation; (i), (j): Human toxicity: cancer; (k), (l): Eutrophication: terrestrial

As concluded in Section 3.2, the steel foil envelope and the other components of the NICOLHy VIP are the main contributors to the NICOLHy VIP's environmental impact. In the analysis presented in Figure 14 and Figure 15, the impacts of other VIP components are excluded, as is stated above – they are identical for the two VIP concepts compared. Hence, the main contributor in this comparative analysis is the steel foil envelope. Considering the conventional VIP, it is evident from Figure 15, that the main contributor of its environmental impacts is the fumed silica core material. An observation from the results on a higher resolution is that in both cases, the material stage is contributing the most to the environmental impacts than any other life cycle stage.

In alignment with the comparison of all sixteen impact categories, for the six more in-depth studied categories, it is evident that only in the category of ozone depletion, the conventional VIP outperforms the NICOLHy VIP. The fumed silica core material is the main contributor to the ozone depletion impact of the conventional VIP.

### 3.4.2 NICOLHy VIP and conventional insulation materials

The following analysis benchmarks the NICOLHy VIP to the conventional insulation materials. For all considered concepts and materials, the potential environmental impacts are presented in Figure 16 as normalized indicators relative to the maximum in each category. As observed in Section 3.1 and Section 3.3, the material with the worst performance from an environmental perspective is silica aerogel. It exhibits the highest impact across all categories.

In comparison with the conventional insulation materials, the NICOLHy VIP has the lowest environmental impact in two impact categories, namely: energy resources: non-renewable and eutrophication (terrestrial). As previously stated, each impact category is considered to be of equal importance. Hence, it can be concluded that EPS foam outperforms the NICOLHy VIP as it results in lower environmental impacts in eleven impact categories. Glass fibre outperforms all considered materials and the NICOLHy VIP in three impact categories (climate change, water use, ecotoxicity: freshwater). However, it can be concluded that the VIP demonstrates a superior environmental performance, as it results in lower impacts than glass fibre in nine impact categories. A comparison of expanded perlite and the VIP reveals that the latter exhibits higher impacts in thirteen impact categories. Moreover, PUR foam and MLI result in higher environmental impacts than the NICOLHy VIP across all impact categories.

Therefore, it is evident that the NICOLHy VIP outperforms all conventional insulation materials except EPS foam.

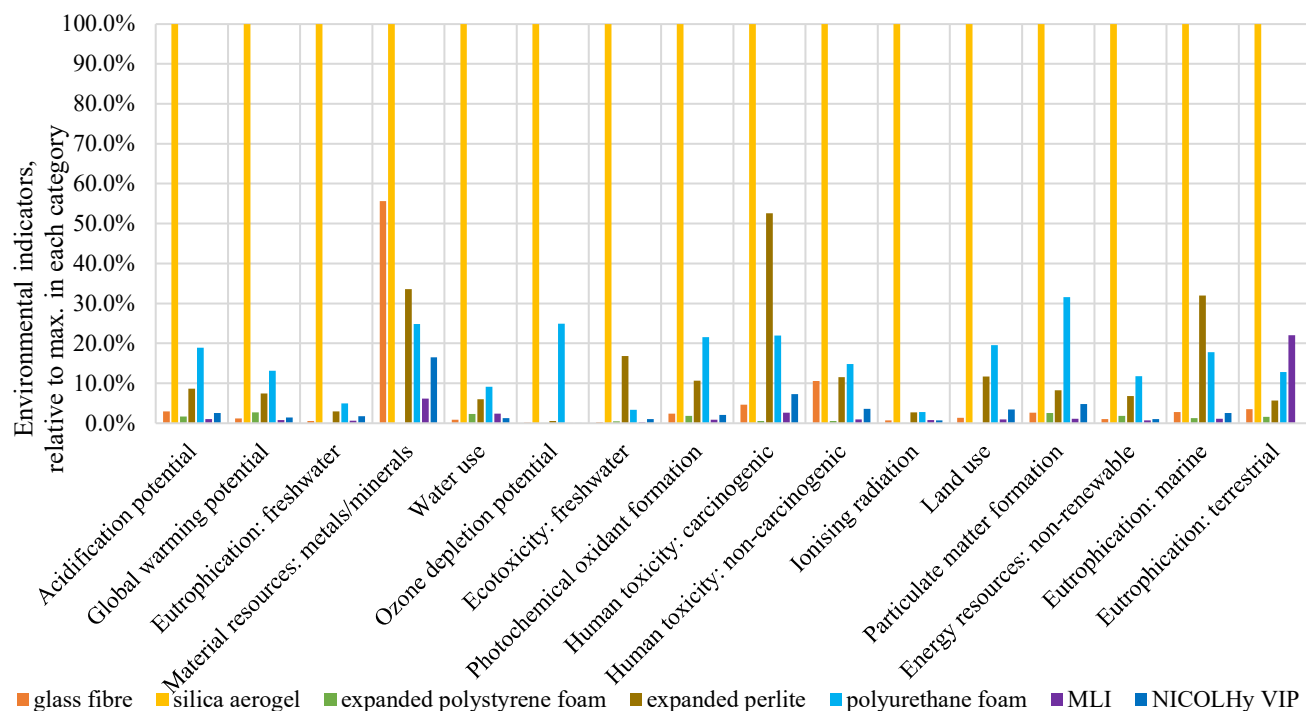
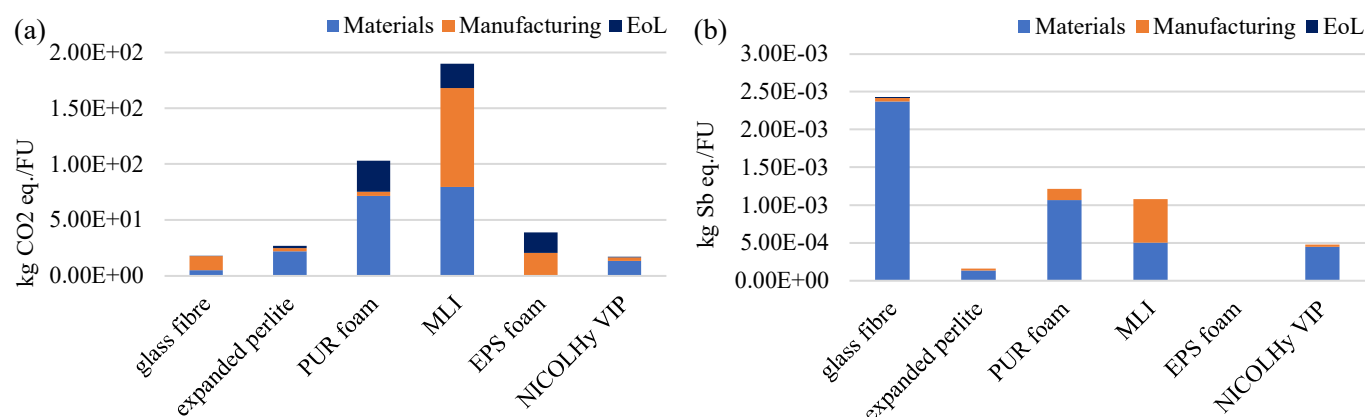


Figure 16: Life cycle impact assessment results from cradle-to-grave of the NICOLHy and the conventional insulation materials glass fibre, silica aerogel, expanded perlite, polyurethane foam, and MLI as indicators relative to the maximum in each category

An in-depth analysis of the life cycle stage (see Figure 17) is carried out with the aid of the six impact categories chosen. Silica aerogel is excluded from the analysis due to its poor environmental performance.



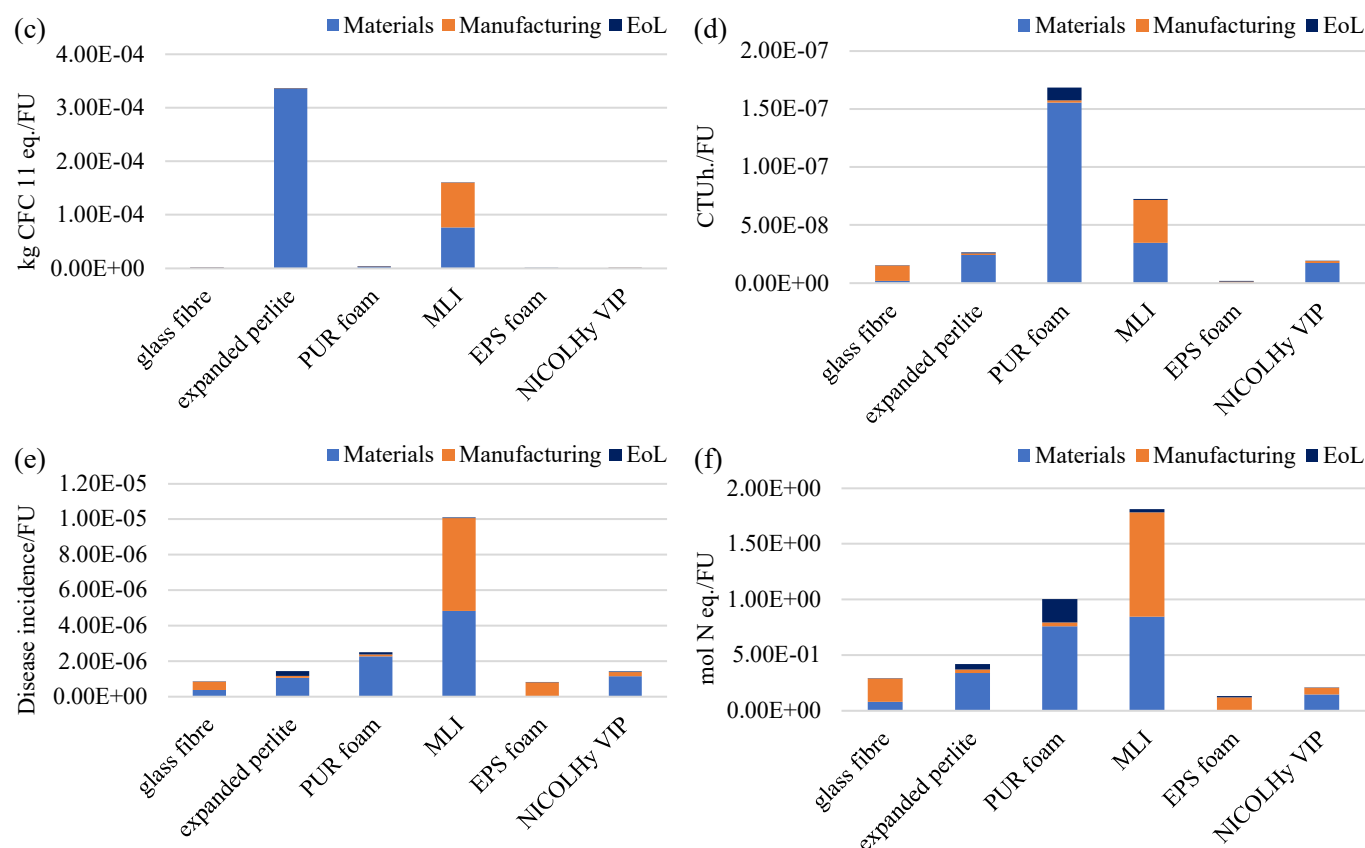


Figure 17: Environmental impacts of NICOLHy VIP and conventional insulation materials and impact categories per functional unit; “Materials” relates to the (raw) material stage, “Manufacturing” relates to the manufacturing stage, and “EoL” to the end-of-life stage; (a): Global warming potential, (b): Material resources: metals/minerals; (d): Ozone depletion potential, (d): Particulate matter formation; (e) Human toxicity: cancer; (f) Eutrophication: terrestrial

As observed in the in-depth analysis of the conventional insulation materials (compare Section 3.3), the material or manufacturing stage is the primary contributor to the environmental impacts. Section 3.3 highlights which conventional insulation materials are most affected by each stage. Specifically, expanded perlite and PUR foam show the highest impact from the raw material extraction stage, while glass fibre, MLI, and EPS foam are most significantly impacted by the manufacturing stage. From the results shown in Figure 10 in Section 3.2, it can be concluded that the material stage is the main driver for the environmental impacts of the NICOLHy VIP.

The in-depth analysis depicted in Figure 17, which explores conventional insulation materials and the NICOLHy VIP, reveals a noteworthy observation: within each of the six impact categories, there is a conventional insulation material that exhibits significantly higher impacts in comparison to the VIP. In climate change, particulate matter formation, and terrestrial eutrophication it is MLI, that has a comparatively high environmental impact. While in material resources: metals/minerals, glass fibre is identified as the material with the poorest performance. Expanded perlite exhibits the highest impact in ozone depletion. A comparatively high impact can be observed in the category of cancerogenic human toxicity for the material polyurethane foam.

### 3.5 Sensitivity study

Sequel to the life cycle impact assessment, a sensitivity analysis involving several scenarios is conducted. These scenarios outlined in Section 2.6, focus on the NICOLHy concept, in accordance with the primary objective of the study.

As stated in Section 3.1, the manufacturing stage is identified as the primary contributor to the environmental impacts of the glass bubbles in majority of the studied impact categories. Consequently, the first two scenarios, with their respective sub-scenarios, concentrate on different energy sources. The results are analysed in two stages. Firstly, the environmental impacts of the glass bubbles are considered (Figure 18 and Figure 19). Secondly, the sensitivity is analysed as part of the environmental impacts of the whole NICOLHy VIP (Figure 20).

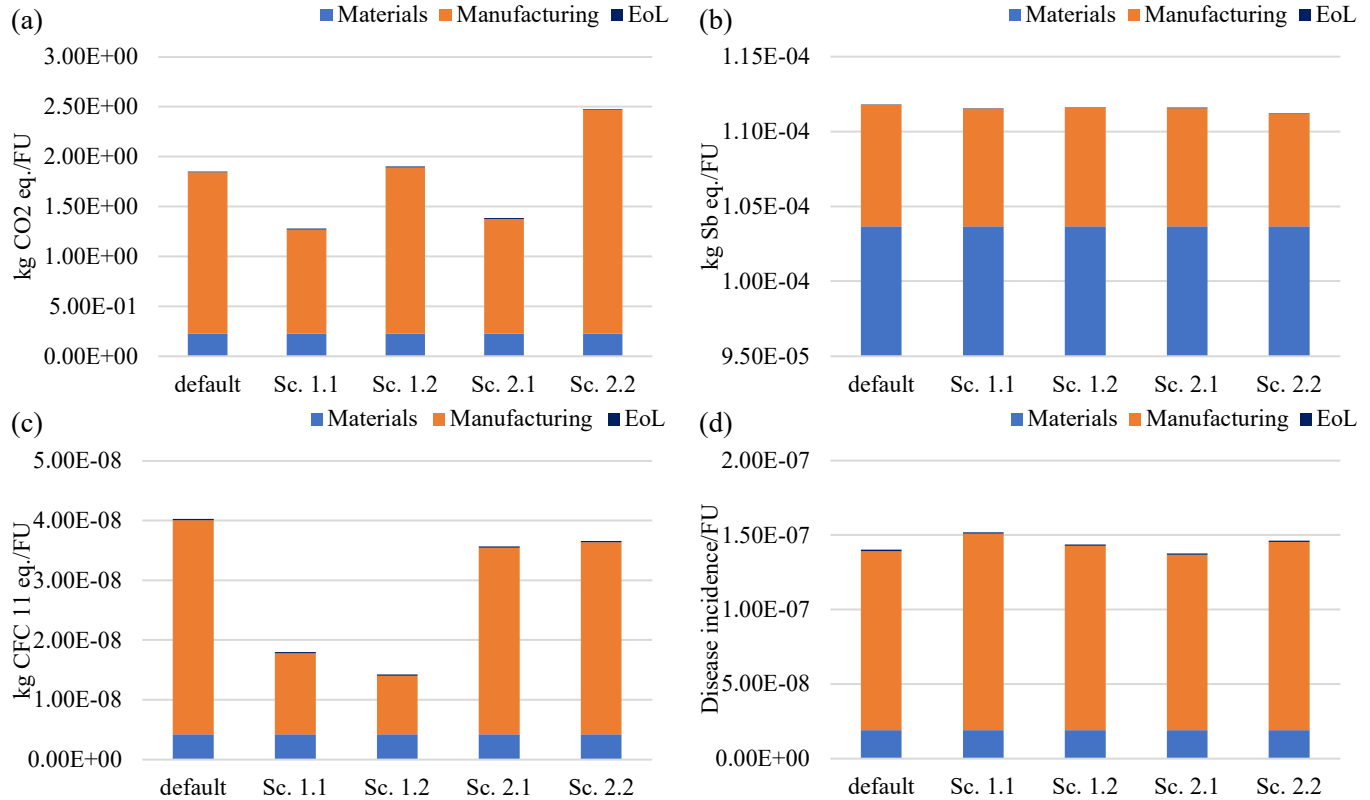


Figure 18: Sensitivity analysis results of the first two scenarios Sc. 1.1 – Sc. 2.2, studying the effects of renewable vs. non-renewable energy sources on the impact of glass bubbles, of selected impact categories per functional unit, showing the results on the level of the life cycle stages of the core material; (a): Global warming potential, (b): Material resources: metals/minerals; (c): Ozone depletion potential, (d): Particulate matter formation

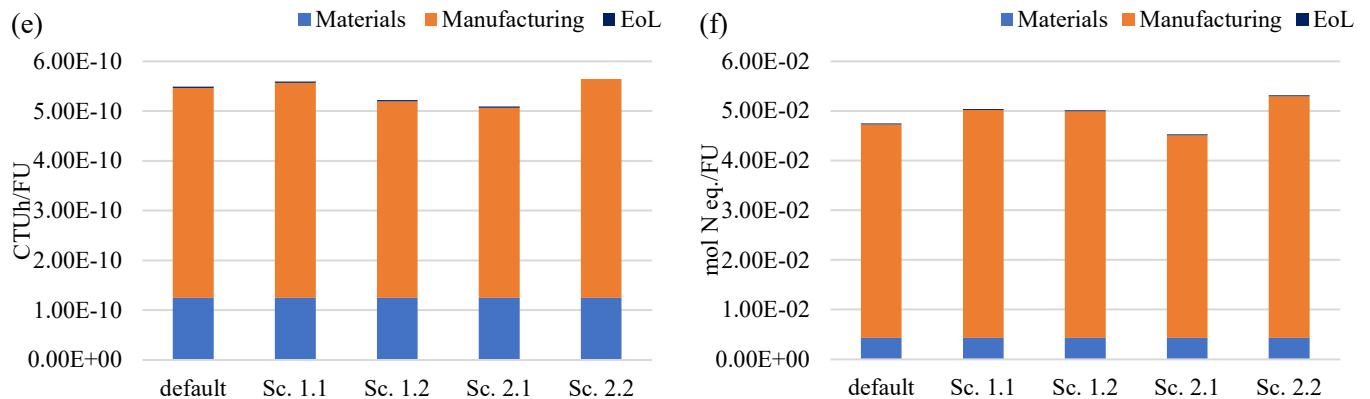
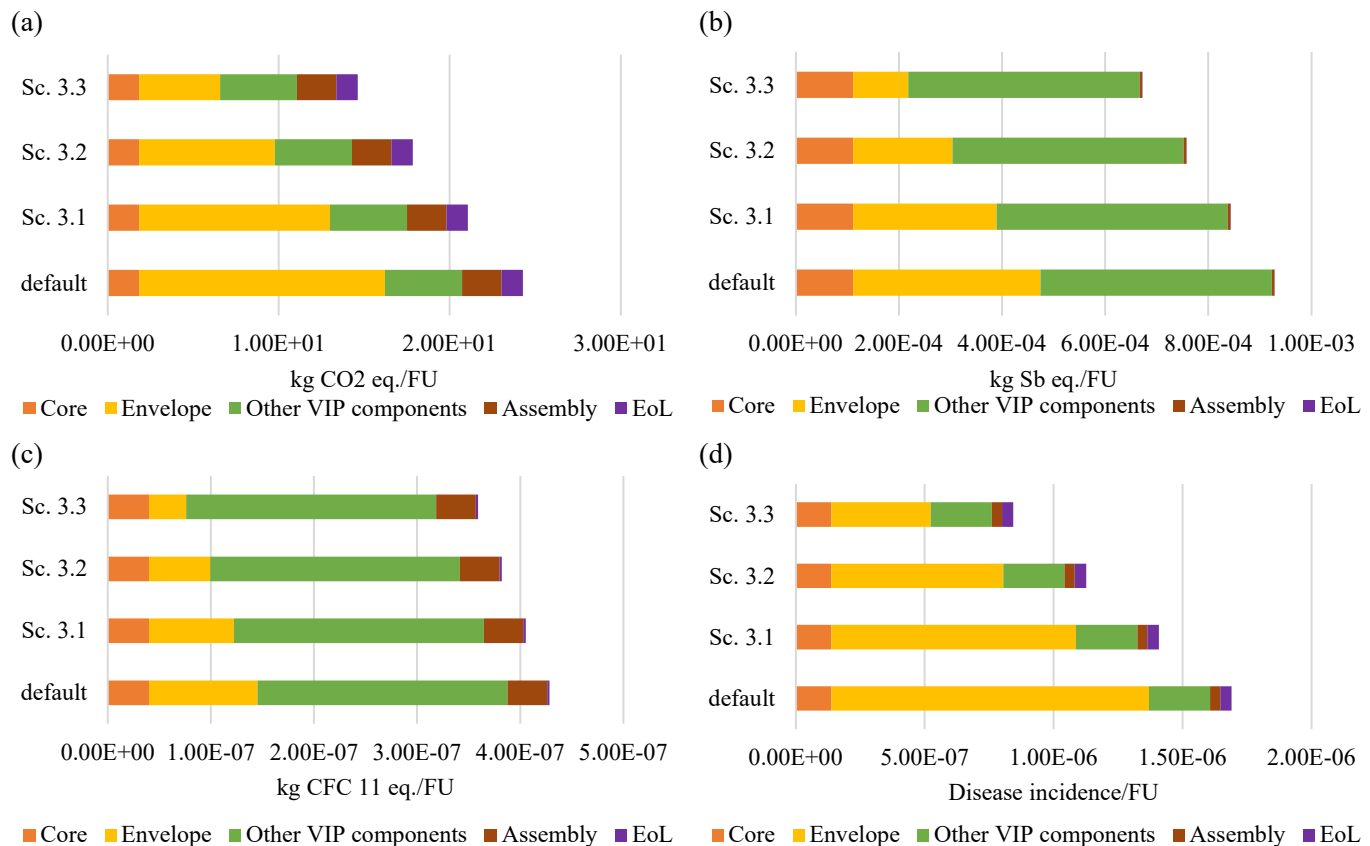


Figure 19: Sensitivity analysis results of the first two scenarios Sc. 1.1 – Sc. 2.2, studying the effects of renewable vs. non-renewable energy sources on the impact of glass bubbles, of selected impact categories per functional unit, showing the results on the level of the life cycle stages of the core material; (e): Human toxicity, cancer; (f): Eutrophication, terrestrial

The results in Figure 19 show that switching to fully renewable heat based on wood-chips (Sc. 1.1) or to fully renewable electricity based on wind-power (Sc. 2.1) shifts the environmental burdens. For the former, the renewable heat, a reduction of the environmental

burden can be observed in the impact categories of climate change, material resources: metals/minerals, and ozone depletion potential. For the latter, a reduction across all impact categories under study is observed. The environmental impact can be reduced by 31% when renewable heat from wood chips is used in the manufacturing of glass, and by 25% when renewable electricity from wind power is applied. Additionally, using renewable heat can lower ozone depletion impacts by 56%, while renewable electricity leads to a 12% reduction. The relative increase in other impact categories due to switching to renewable heat remains below 10%. However, it's important to emphasize that all impact categories are considered equally significant in this study. Therefore, it is not appropriate to claim that, for example, the reduction in ozone depletion from switching to renewable heat outweighs the increase in particulate matter formation.

With regard to the utilisation of non-renewable energy sources in the manufacture of glass bubbles, an increase can be observed in both the heat and the electricity scenarios (1.2 and 2.2, respectively) in the impact categories of climate change, particulate matter formation, and terrestrial eutrophication. Conversely, a reduction can be observed in the categories of material resources, and ozone depletion potential. In the impact category of cancerogenic human toxicity, an increase may be observed in the case of hard-coal-based electricity, while a decrease may be observed in the case of hard-coal-based heat. However, the increase in global warming is only significant when non-renewable electricity (34%) is used, while it is minor (3%), in the case of heat. Furthermore, the reduction in ozone depletion potential is only significant in one of the two considered scenarios, namely the non-renewable heat source (65%), while it is minor (9%) in the case of electricity.



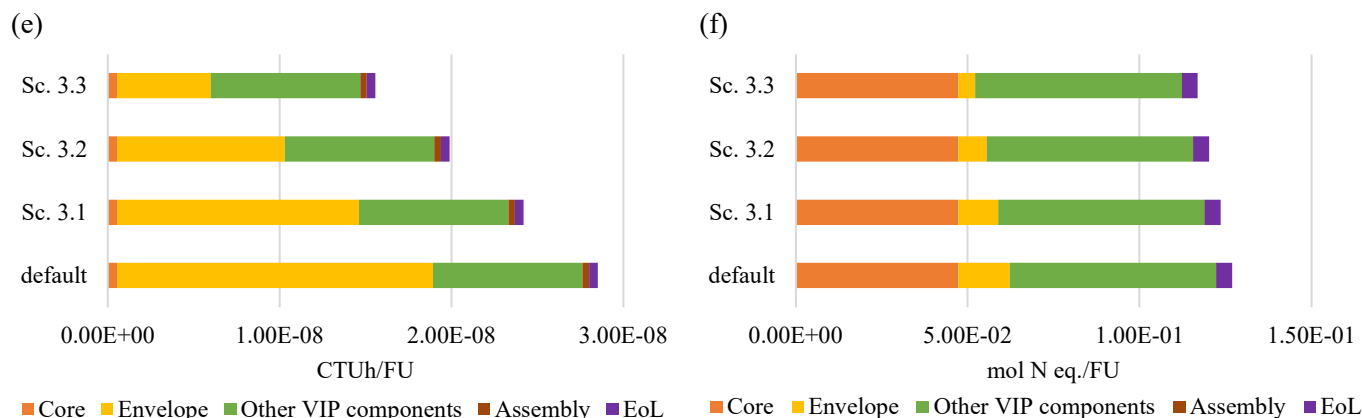
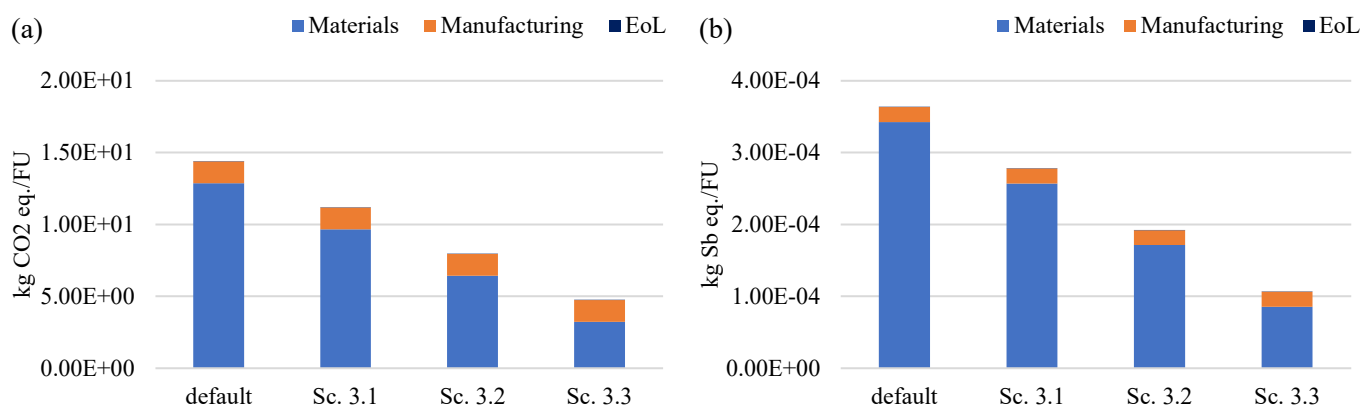


Figure 20: Sensitivity analysis results of the first two scenarios Sc. 1.1 – Sc. 2.2, studying the effects of renewable vs. non-renewable energy sources on the impact of glass bubbles, of selected impact categories per functional unit, showing the results on the VIP level; (a): Global warming potential, (b): Material resources: metals/minerals; (c): Ozone depletion potential, (d): Particulate matter formation; (e): Human toxicity, cancer; (f): Eutrophication, terrestrial

Considering the results of the first two scenarios with their respective sub-scenarios as part of the life cycle impact of the whole VIP, the influence of changing the energy source is reduced. While the reduction of the climate change impact is 31% for the renewable heat sources on the overall impact of the glass bubbles life cycle, the reduction is 2.5% on the overall impact of the whole VIP's life cycle. This is in line with the scope that is comparatively narrow when considering the glass bubbles only. Similar observations hold for the remaining scenarios; hence, no further analysis is required.

The third scenario examines the influence of steel's circularity. As outlined in Section 2.6, three scenarios are considered, each characterised by different rates of recycled steel in the steel production. Firstly, consideration is given to the impacts of the life cycle of the steel foils, separate from the impacts of the VIP (Figure 21). This is followed by studying them in terms of the life cycle impacts of the whole VIP (Figure 22).



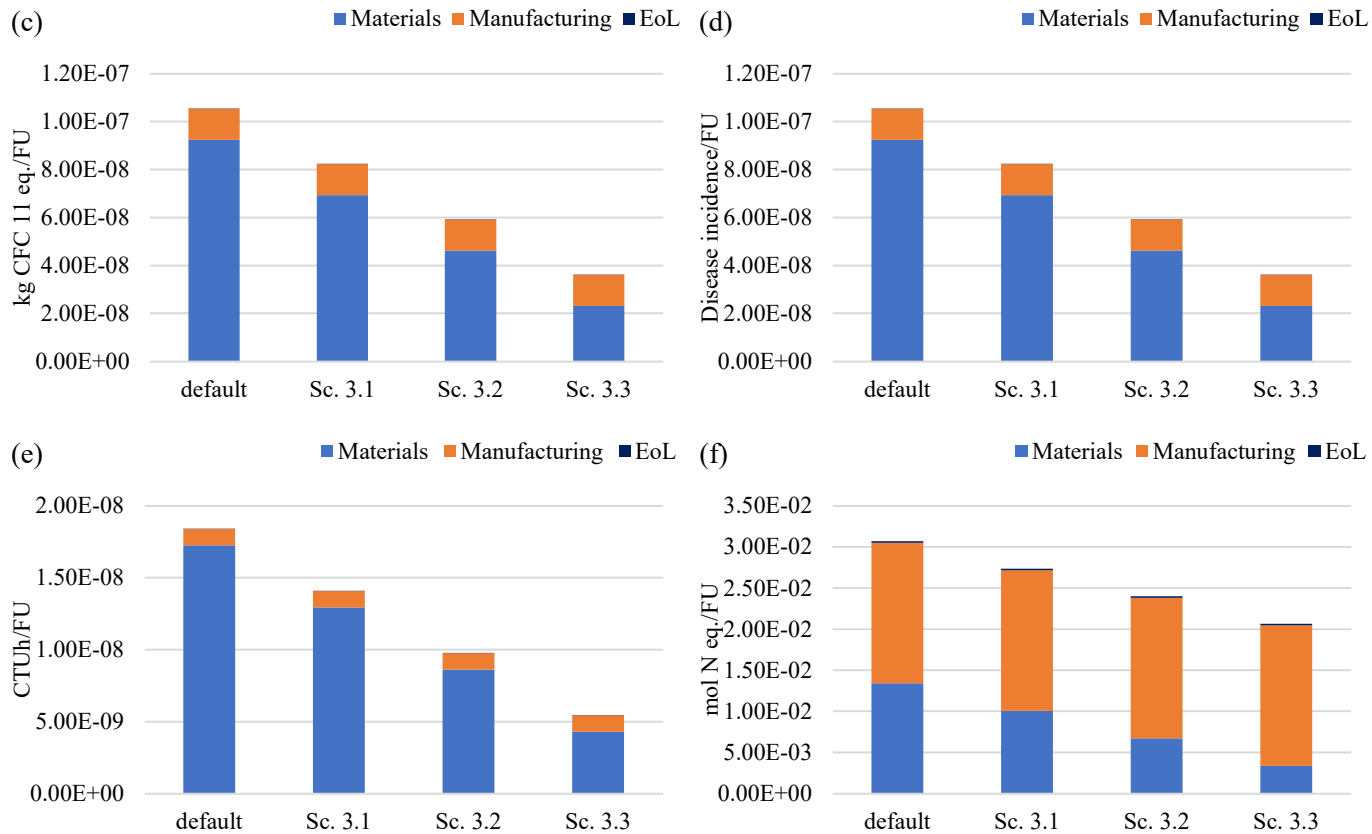


Figure 21: Sensitivity analysis results of the first two scenarios Sc. 3.1 – Sc. 3.3, studying the effects of different rates of recycled steel (0%, 25%, 50%, 75% of recycled steel in the steel foil manufacture) on the impact of the steel foil, of selected impact categories per functional unit, showing the results on the level of the life cycle stages of the envelope material; (a): Global warming potential, (b): Material resources: metals/minerals; (c): Ozone depletion potential, (d): Particulate matter formation; (e): Human toxicity, cancer; (f): Eutrophication, terrestrial

From Figure 21 a trend can be observed, indicating a reduction in environmental impacts across all categories. Consequently, an increase in the utilisation of recycled steel is associated with a reduction in environmental impact. A reduction in impact of between 21.9% and 23.6% can be observed when 25% of recycled steel is employed in the steel foil's life cycle. An impact reduction of 43.8% to 47.1% is obtained in the case of 50% recycled steel, while a reduction of 65.7% to 70.7% can be seen when 75% of recycled steel is utilised. The range of impact reductions is to be explained by the different influence the material stage has on the overall life cycle of the steel foil.

In relation to the methodology employed in the modelling of steel recycling, it is important to acknowledge the adoption of the ecoinvent cut-off approach. Consequently, the utilisation of the recycled materials does not impose any burden on the user of the recycled material, only the further processing of the material must be accounted for [30]. Hence, any additional impacts that may arise from a more circular recycling chain, for instance, a higher demand for collection schemes, are not considered.

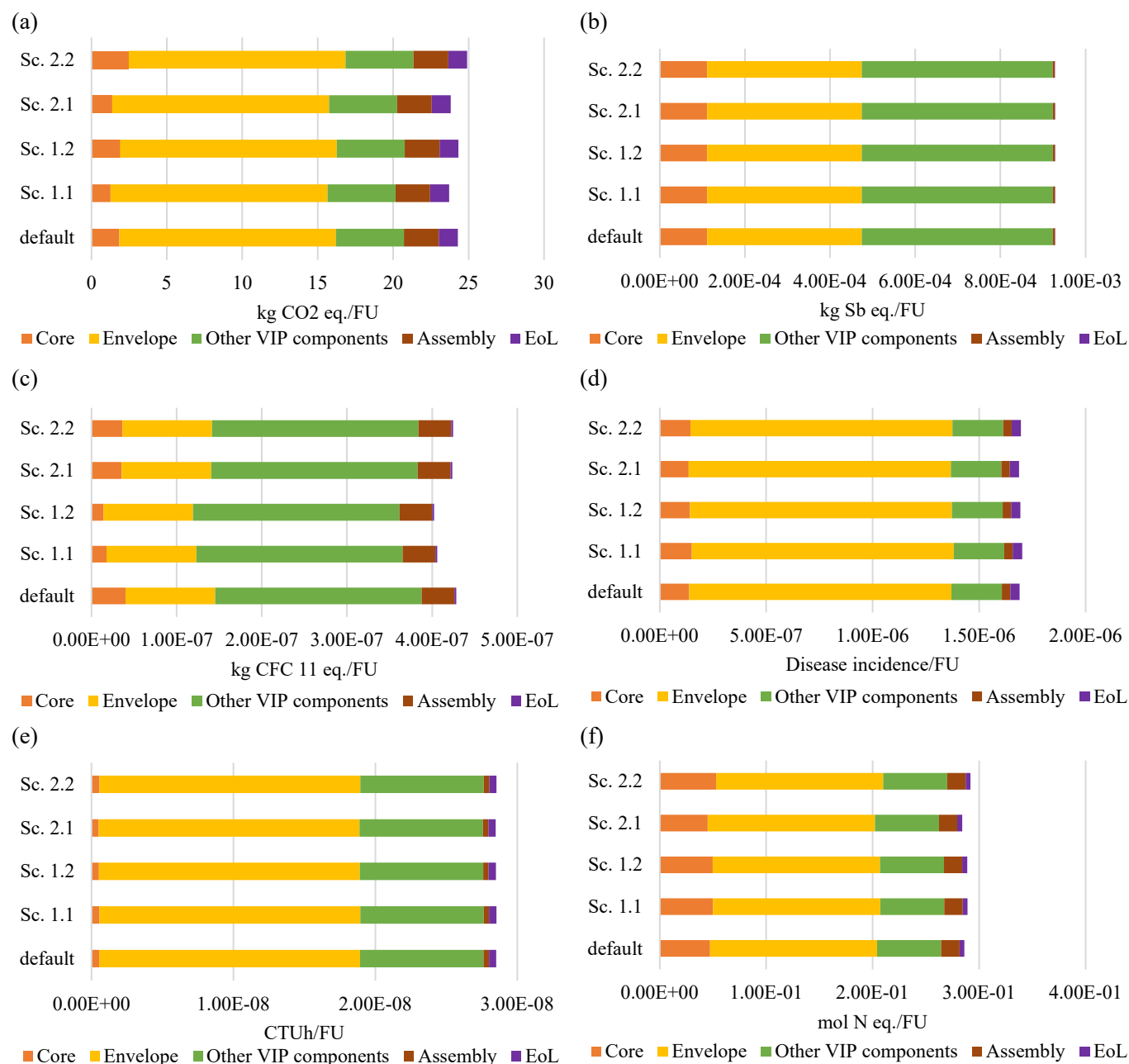


Figure 22: Sensitivity analysis results of the first two scenarios Sc. 3.1 – Sc. 3.3, studying the effects of different rates of recycled steel (0%, 25%, 50%, 75% of recycled steel in the steel foil manufacture) on the impact of the steel foil, of selected impact categories per functional unit, showing the results on the VIP level; (a): Global warming potential, (b): Material resources: metals/minerals; (c): Ozone depletion potential, (d): Particulate matter formation; (e): Human toxicity, cancer; (f): Eutrophication, terrestrial

Studying the results of the third scenario of the sensitivity analysis as part of the life cycle impact of the whole VIP shows that the influence of increasing the amount of recycled steel in the manufacture of the steel foil is reduced. The utilisation of 25% recycled steel results in an impact reduction of 5% to 17%, while utilising 50% of recycled steel results in a reduction of 11% to 34%, and utilising 75% leads to a reduction of 16% to 51%.

In comparison with the sensitivity study of the glass bubbles, it can be stated that the influence of the steel foil is higher. The differences in impact reduction between the same percentages of recycled steel in different impact categories can be attributed to the varying influence the steel foil has on the score of certain impact categories. For instance, the lowest environmental impact reduction is observed in ozone depletion. This finding aligns with the observation

documented in Section 3.2, which concluded that the steel foil does not represent the primary contributor to the VIP's ozone depletion impact. The highest impact reduction is seen in particulate matter formation. This is also in line with the findings from Section 3.2, as it is determined to be the primary contributor to the VIP's life cycle impacts in this category.

In summary, it has been shown that a change in the energy sources utilised in the manufacture of glass bubbles can result in a minor reduction in the VIP's environmental impacts. However, the focus should be on the utilisation of recycled steel, given that the impact of the steel foil on the VIP's life cycle is more significant than that of glass bubbles.

### 3.6 Uncertainty analysis

In addition to the sensitivity analysis, the uncertainty of the NICOLHy VIP and the conventional VIP is studied. The uncertainty analysis is performed only for climate change due to its significant societal relevance.

In the present study, the input uncertainties are propagated using a Monte Carlo simulation with 2500 iterations. The results are shown in Figure 23.

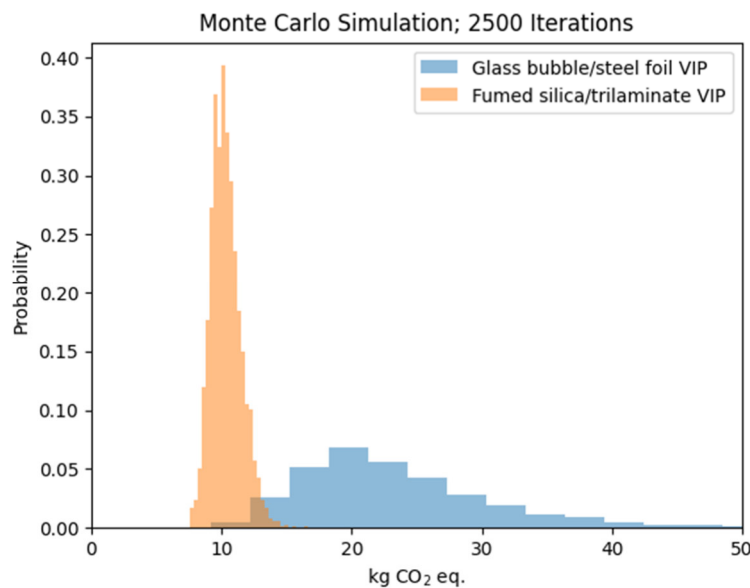


Figure 23: Uncertainty distributions based on the Monte Carlo Simulation for the novel and the state-of-the-art VIPs for the impact category climate change

As illustrated in the figure, the conventional VIP is generally expected to have a lower global warming impact than the NICOLHy VIP. The conventional VIP shows a mode of 10.16 kg CO<sub>2</sub> eq., and a mean of 10.36 kg CO<sub>2</sub> eq., while the NICOLHy VIP has a mode of 19.74 kg CO<sub>2</sub> eq. and a mean of 23.45 kg CO<sub>2</sub> eq. Furthermore, the variability of the underlying data is lower for the conventional VIP. That notwithstanding, there is a possibility that both VIPs have the same climate impact or that the NICOLHy VIP has a lower impact. This is indicated by the overlapping area of the two histograms shown in Figure 23.

## 4 Interpretation and Discussion

In the following, the results presented in Chapter 3 are interpreted and discussed.

### *VIP core materials*

The LCA results show that the VIP core material with the best performance from an environmental standpoint is expanded perlite, followed by glass bubbles, glass fibre, and fumed silica. The worst performance is exhibited by silica aerogel, followed by polyurethane foam. Hence, silica aerogel and polyurethane foam are the worst options from an environmental perspective and are not recommended to be employed as VIP core material for cryogenic applications. Consequently, the remaining four materials are recommended. With regard to the life cycle stages, it is concluded that the manufacturing of the glass-based materials is the main contributor to the environmental burden, whereas for expanded perlite and fumed silica, the material stage is the main driver.

### *VIPs*

The LCA results of the NICOLHy VIP identify the steel foil envelope as the main environmental hotspot, followed by other potential components of the VIP, such as sensors or opacifiers. The results of the conventional VIP demonstrate that the fumed silica core is the main contributor to the environmental burden. The latter aspect aligns with the findings from [7], [5], or [6], where it was demonstrated that the core material is the main contributor to the environmental impacts of a conventional VIP. Hence, a difference in the contribution of the constituents of a VIP can be concluded for the NICOLHy VIP, designed for cryogenic applications, and a conventional VIP.

### *Conventional insulation materials*

The conventional insulation materials studied include materials that can be used as VIP core materials. The difference in the assessment undertaken is that the insulation materials are studied under ambient pressure conditions. Whereas the insulation materials that may be used as VIP core materials are studied under vacuum pressure. This is due to the scope, as the VIPs themselves are studied under ambient pressure conditions; hence, for the comparison, this is the condition for the insulation materials as well. From the LCA results, it is found that EPS foam exhibits the lowest environmental impacts, while silica aerogel exhibits the highest impacts. Comparing MLI, expanded perlite and PUR foam, they all perform better than silica aerogel. However, MLI performs worse than PUR foam and expanded perlite, with expanded perlite being the second most environmentally sustainable option.

### *Benchmarking study*

In comparison with the conventional insulation materials, the NICOLHy VIP can be concluded to be outperformed by EPS foam, as it results in higher environmental impacts in the majority of the impact categories studied. However, the NICOLHy VIP outperforms the remaining conventional insulation materials, which are glass fibre, expanded perlite, PUR foam, and MLI in the majority of the impact categories studied.

Comparing the NICOLHy to the conventional VIP, the latter results in lower environmental impacts. Hence, the conventional VIP is the preferable option from an environmental perspective.

### *Sensitivity analysis*

The sensitivity study showed that the most dominant reduction in the environmental impact of the NICOLHy VIP can be achieved via the utilisation of recycled steel. This is in line with the fact that the steel foil is one of the main contributors to the impacts of the NICOLHy VIP. In addition, a reduction of the NICOLHy VIP's impacts can be achieved via the use of renewable electricity sources in the glass bubble production processes. However, the influence is small in comparison with the steel foil. Furthermore, the use of renewable heat in the manufacture of the glass bubbles can result in a shift of environmental burdens between impact categories.

#### *Uncertainty analysis*

The uncertainty analysis revealed that the data quality of the NICOLHy VIP is lower than that of the conventional VIP. Hence, further data collection efforts should focus on improving the data quality of the NICOLHy VIP. Another observation is that there is little probability that both concepts result in the same or that the NICOLHy VIP results in a lower GWP. With regards to the uncertainty analysis, the scope may be broadened, as during data collection, the following two aspects were noted: the data for the silica aerogel is based on pilot-scale data. For the assessment, it is assumed that the data quality is sufficient, due to silica aerogel not being the primary subject of the study. Furthermore, there is a range of aerogel types and manufacturing pathways that all result in a range of different environmental impacts. Another aspect with regard to data quality is the MLI. Similarly, there is a range of different MLIs, and the data sources for the LCI and the thermal conductivity data may not all relate to the same MLI type.

## 5 Conclusion

This study investigated the environmental sustainability of insulation materials and concepts for cryogenic LH<sub>2</sub> storage tank applications. Six different core materials for vacuum insulation panels, a novel VIP, a conventional VIP, and six conventional cryogenic insulation materials were studied. A cradle-to-grave life cycle assessment was performed to identify the most environmentally sustainable insulation design. This was done by first assessing the VIP core materials, the novel NICOLHy VIP concept, and the conventional insulation materials individually. The NICOLHy concept was benchmarked with a conventional VIP and conventional insulation materials. Out of the six VIP core materials, expanded perlite demonstrated to be the most sustainable choice from an environmental perspective, followed by glass bubbles, glass fibre and fumed silica. The worst-performing materials were found to be silica aerogel, followed by polyurethane foam. Hence, the latter two are not recommended from an environmental perspective. With regards to the NICOLHy VIP, which consists of a glass bubble core and a steel foil envelope, it was found that the primary contributor to its environmental impact is the steel foil, followed by other VIP components that may be included (sensors, opacifiers, etc.). In comparison with a conventional VIP based on a fumed silica core and a trilaminate foil envelope, the NICOLHy concept was outperformed by the conventional VIP in the majority of the impact categories under study. In comparison with conventional insulation materials, however, the NICOLHy VIP was only outperformed by one of the six investigated materials (EPS foam). The remaining materials, glass fibre, expanded perlite, PUR foam, and MLI, resulted in higher environmental impacts than the NICOLHy VIP in the majority of the considered impact categories. Moreover, the overall environmental performance of the novel concept can be significantly improved by using recycled steel in the manufacture of the steel foil. A minor improvement is possible via the utilisation of a fully renewable electricity source in the production of glass bubbles. Finally, the environmental sustainability of insulation materials and concepts is not the only criterion required for selecting the most appropriate concept. In addition, it is essential to consider other requirements, such as thermal and mechanical performance.

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