International Energy Agency

Long-Term Performance of Super-Insulating Materials in Building Components and Systems

Energy in Building and Communities Programme

Holger Wallbaum (Editor)

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International Energy Agency, EBC Annex 65

Long-Term Performance of Super-Insulating Materials in Building Components and Systems

Report of Subtask IV: Sustainability

Life Cycle Assessment : LCA - Life Cycle Cost : LCC

Embodied Energy : EE

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 28 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates research and development in a number of areas related to energy. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)

Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Thermal Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)
Annex 56: Cost Effective Energy & CO_2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy & CO_2 Equivalent Emissions for Building Construction
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements
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Annex 65: Long Term Performance of Super-Insulating Materials in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behavior Simulation
Annex 67: Energy Flexible Buildings
Annex 68: Design and Operational Strategies for High IAQ in Low Energy Buildings
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

Summary

This report of the International Energy Agency (IEA) Annex 65 subtask 4 considers a few selected but relevant means of assessing the current sustainability performance of Super-Insulating Materials (SIMs) namely the Life Cycle Assessment (LCA), the Life Cycle Cost calculation (LCC), and the Embodied Energy (EE). Subtask 4 of IEA Annex 65 investigated the existing studies on LCA on super insulation materials (SIMs), according to the product categorization agreed by the Annex. After mapping the current state, the subtask constructed a life cycle inventory (LCI) of SIMs to make a transparent assessment of the environmental performance of a range of SIMs. Based on this LCI, a life cycle impact assessment (LCIA) of SIMs was also conducted. Contribution analysis was conducted to highlight the hotspots of the environmental performance of SIMs and a comparison between the conventional thermal insulation materials is shown. The SIMs examined in IEA Annex 65 are advanced porous materials (APMs) and vacuum insulation panels (VIPs).

The original approach of this subtask was to construct this transparent LCI through cooperation with the manufacturers. However, this approach was unable to be implemented due to various challenges including resolving concerns over confidentiality issues. This led the subtask to develop the LCI based on the existing literature.

The LCIA of VIP showed a good level of coherency with the published Environmental Product Declarations (EPDs), which normally does not contain transparent LCI information. The result creates a solid basis for the comparison with conventional insulation materials for other LCIA studies.

Meanwhile, the LCIA result of aerogel (the APM examined) showed a large difference between published EPDs. This was due to the fact that the available LCI information only represented the pilot scale. Although EPDs represent product-specific LCIA results, the level of information described in the document may not always be sufficient to allow a fair comparison. This lack of transparency remains a challenge for new advanced materials.

A hypothetical case of renovation which looked into the economic and the environmental payback time showed that SIMs have very long simple payback times in most northern European cities. However, places with high land price or high heating demand can affect the competitiveness of the SIMs, both economically and environmentally. In reality, there are various limitations that may affect the decision of insulation material selection. Cases where space limitations are given, or preservation of the architectural design were seen as reasons for implementing the SIMs in the existing building renovation projects.

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1 Introduction

As part of the Construction Product Regulation (CPR) (European Parliament, 2011)[1], product-specific information on environmental impact as well as sustainable use of natural resources is required as Basic Requirements (BR). To fulfil the requirements, life cycle assessment (LCA) can provide such product specific information.

One persistent challenge is a lack of transparent datasets on the LCA input data for advanced materials in public or well-known commercial life cycle inventory (LCI) databases (NTUA, 2016). Since not all product-specific environmental impacts are currently available, representative datasets can play an important role, for both manufacturers and building designers to improve the estimate of the environmental impact of a building and its constituent materials.

Subtask 4 of IEA Annex 65 reviewed existing LCA studies on super insulation materials (SIMs). After mapping the current state, the subtask constructed a life cycle inventory (LCI) of SIMs to make a transparent assessment of the environmental performance of a range of SIMs. The SIMs examined in IEA Annex 65 are **advanced porous materials (APMs)**, such as aerogels and **vacuum insulation panels (VIPs)**. The building of subtask-specific LCIs followed the following procedure:

1. Literature review
2. Questionnaire on available EPDs of SIMs
3. Draft of production processes to be revised/complemented by participating SIM producers
4. Drafting of Annex 65 LCIs, which have been sent for review to participating SIM producers
5. Online meetings with detailed feedback opportunities for subtask 4 working group
6. Final Annex 65 LCIs that have been used to conduct the life cycle impact assessments (LCIAs) that built the basis for the results presented in this report
7. Contribution analysis has been conducted to highlight the hotspots of the environmental performance of SIMs and comparisons are shown between SIMs and conventional thermal insulation materials.

[1] The regulation became effective in 2012 for new products and 2013 for existing products.

2 Status quo of Life Cycle Assessment, Embodied energy and Life Cycle Cost Assessment

LCA is an ISO certified assessment framework that quantifies the environmental impact of products or services over their life cycles. According to ISO14040 (International Organization for Standardization, 2006), “LCA can assist in

- identifying opportunities to improve the environmental performance of products at various points in their life cycle,
- informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),
- the selection of relevant indicators of environmental performance, including measurement techniques, and
- marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).”

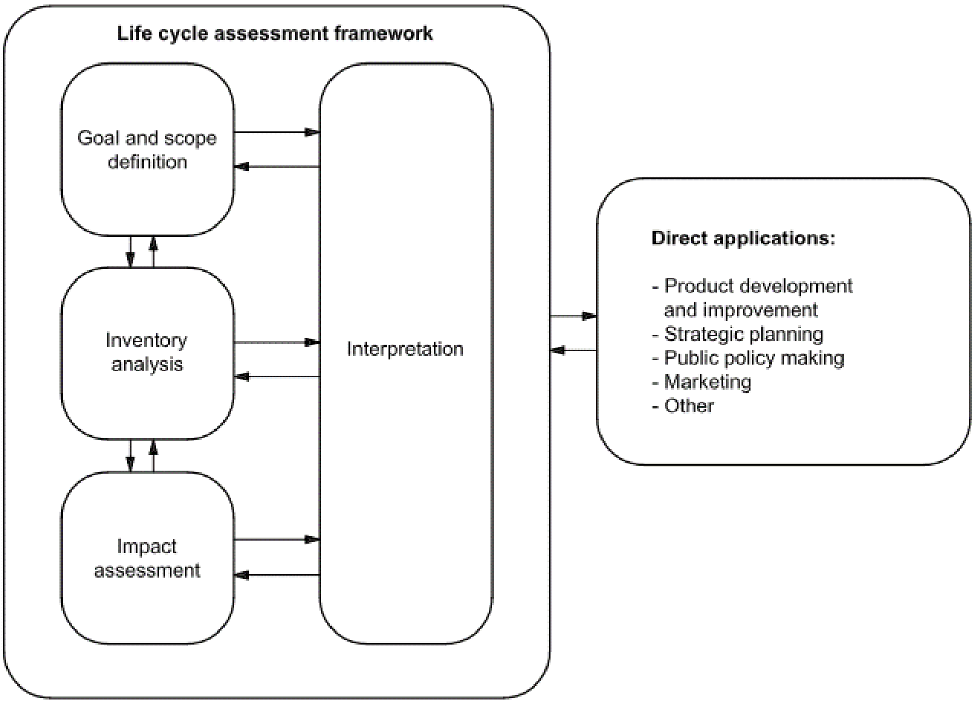

Figure 1. Illustration of stages of LCA according to ISO 14040 (International Organization for Standardization, 2006)

As illustrated in Figure 1, the LCA study consists of four phases 1) identify the goal and define the scope, 2) conduct an inventory analysis, 3) conduct an impact assessment and 4) interpret the results. For the impact assessment phase in LCA, there are three ‘Areas of Protection’: 1) human health, 2) natural environment and 3) natural resources

(Hauschild et al., 2011). Depending on the goal and scope of the study, the relevant Area of Protection may change which affects the choice of the impact assessment method. Therefore, the first phase of LCA is a crucial step because it defines what and how to compare and which types of impact to consider.

For construction products, European Standard EN 15804 provides calculation rules for the assessment of the environmental performance on a product level (European Committee for Standardization, 2013). This standard harmonizes the rules for Environmental Product Declarations (EPD) of construction products and services which plays a vital role to carry out the assessment on a building scale. One of the defined contents in EN 15804 is the life cycle stage module that is shown in Table 1. The system boundary that covers A1-A3 is typically called “Cradle-to-Factory gate”, while the one covering A1-C4 is referred to as “Cradle-to-Grave”. The one that includes D module is called “Cradle-to-Cradle”.

<table>
<tr><th colspan="3">Life cycle stage modules</th><th>Name of the sub-module</th></tr>
<tr><td rowspan="16">Building life cycle information</td><td rowspan="3">PRODUCT stage</td><td>A1</td><td>Raw material supply</td></tr>
<tr><td>A2</td><td>Transport</td></tr>
<tr><td>A3</td><td>Manufacturing</td></tr>
<tr><td rowspan="2">CONSTRUCTION PROCESS stage</td><td>A4</td><td>Transport</td></tr>
<tr><td>A5</td><td>Construction, installation processes</td></tr>
<tr><td rowspan="7">USE stage</td><td>B1</td><td>Use</td></tr>
<tr><td>B2</td><td>Maintenance</td></tr>
<tr><td>B3</td><td>Repair</td></tr>
<tr><td>B4</td><td>Replacement</td></tr>
<tr><td>B5</td><td>Refurbishment</td></tr>
<tr><td>B6</td><td>Operational energy use</td></tr>
<tr><td>B7</td><td>Operational water use</td></tr>
<tr><td rowspan="4">END OF LIFE stage</td><td>C1</td><td>De-construction, demolition</td></tr>
<tr><td>C2</td><td>Transport</td></tr>
<tr><td>C3</td><td>Waste processing</td></tr>
<tr><td>C4</td><td>Disposal</td></tr>
<tr><td>Suppl. information beyond the life cycle</td><td>Benefits and loads beyond the system boundary</td><td>D</td><td>Reuse-, recovery- and/or, recycling potentials- potential</td></tr>
</table>

Table 1 Life Cycle Stage Module of Buildings according to EN 15804

2.1 Existing studies of LCA on SIMs

Several LCA studies have been published on SIMs. This includes scientific reports, journal publications and EPDs. Table 2 summarises existing studies on SIMs.

SIM	Institution	Title of project / product name	year	document type	Building life cycle information															
					Product stage			Construction stage		Use stage							End-of-life stage				
					A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
VIP	CSTB	Clear-up	2012	LCA study	O	O	O	-	-	-	-	-	-	-	O	-	-	-	-	-	-
VIP	Morgan Advanced Materials, Porextherm Dämmstoffe	Vacupor NT-B2-S	2014	EPD	O	O	O	-	-	-	-	-	-	-	-	-	-	O	O	O	O
VIP	Fraunhofer etc.	Development of Super Vacuum Insulating Panels and Product Integration Services	2004	LCA study	O	O	O	-	-	-	-	-	-	-	-	-	-	O	O	O	O
VIP	Microtherm	SlimVac	2013	EPD	O	O	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VIP	DOW Corning	Vacuum Insulation Panel	2013	EPD	O	O	O	-	-	-	-	-	-	-	-	-	-	O	O	O	O
VIP	D'Appolonia	FC-DISTRICT	2012	LCA study	O	O	O	-	-	-	-	-	-	-	-	-	-	O	O	O	O
VIP	KTH	A comparative study of the environmental impact of Swedish residential buildings with vacuum insulation panels	2015	LCA study	O	O	O	-	-	-	-	-	-	-	-	-	-	O	O	O	O
aerogel	Aspen Aerogels	Spaceloft grey/white	2013	EPD	O	O	O	O	-	-	-	-	-	-	-	-	-	-	-	-	-
aerogel	Aspen Aerogels	Spaceloft A2	2013	EPD	O	O	O	O	-	-	-	-	-	-	-	-	-	-	-	-	-
aerogel	Brunel University	Novel Retrofit Technologies Incorporating Silica Aerogel for Lower Energy Buildings	2012	LCA study	O	O	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-
aerogel	Fixit	Fixit 222 Aerogel High performance insulating render	2015	EPD	O	O	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-
aerogel	VTT	Aerocoin	2014	LCA study	O	O	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-
aerogel	SINTEF	The Influence of Different Electricity-to-Emissions Conversion Factors on the Choice of Insulation Materials	2014	LCA study	O	O	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-
aerogel	BFE	QualiBOB	2016	LCA study	O	O	O	-	-	-	-	-	-	-	-	-	-	O	O	O	-

Table 2 Summary of LCA studies on SIMs

(in the column "document type"yellow highlights assessed EPDs,
green is used to highlight the life cycle stages covered in the respective study.

As of February 2016, 14 LCA-based studies (EPDs and LCA studies) had been published. Slightly more studies were conducted of VIPs than for APMs. The notable difference among the LCA studies on SIMs is the applied system boundary. For VIP, there are three EPDs and four LCA studies available. All studies cover the production stage A1-A3 and the majority of those studies cover the End-of-Life stages C2-C4 as well as D. One LCA study on VIP covers even the use stage B6 but excluded the End-of-Life. Whereas for APMs (aerogel), only one of the studies covered C modules.

2.2 International projects on LCA of SIMs

2.2.1 VIP

Most international LCA studies on VIP were made after 2010, one investigating the reduction of energy consumption in existing buildings (Clear-up) and another looking at state-of-the-art and innovative technology for district heating pipes (FC-District).

2.2.2 APM

LCA studies on APM covered only aerogels. One of the studies was a European Commission-funded project, which finished in 2015. The Swiss project (QualiBOB) included aerogel and was published in 2016.

2.3 EPD of SIMs

2.3.1 VIP

Since several VIP products are out in the market as construction materials, there are a few EPDs publicly available. As of February 2016, there were 3 EPDs of VIP from 3 different manufacturers, which were declared for Belgium, the US and Germany. The 3 declarations were published in 2013 and 2014, 2 of the declarations included C modules (Cradle-to-grave) based on the Life Cycle Module from EN 15804.

2.3.2 APM

For APM, 3 EPDs from 2 aerogel manufacturers were published as of February 2016. The declarations were released in 2013 and 2015 in the US and Switzerland. Two of the declarations were from the US and covered the A1-A4 modules, while the one from Switzerland covered A1-A3 (Cradle-to-gate).

2.4 LCA on SIMs application

2.4.1 VIP

Among the collected studies, there were two scientific articles that reported an LCA of VIP application in buildings. One study was from Norway (Lolli & Hestnes, 2014) on retrofitting a residential building which looked into the carbon emissions of the building with different scenarios of electricity grid mix, as well as the energy demands that depend on the retrofit option. The retrofit option for insulation materials includes aerogel, VIP and Rockwool. Another study from Sweden (Karami, Al-Ayish, & Gudmundsson, 2015) conducted an LCA of residential buildings with a broader scope of environmental impacts. The study investigated the application of VIP to residential buildings compared to traditional insulation materials, including mineral wool and expanded polystyrene (EPS).

The conclusions from both studies were that the life cycle carbon emission of the building using the VIP did not outperform the building with conventional insulation material when the thermal performance of the materials was aligned (the functional unit of the two insulation materials have been brought to the same thermal performance level to make the comparable). Both studies investigated A1 to C modules for carbon emission which takes the operational phase into account.

2.4.2 APM

The study in Norway (Lolli & Hestnes, 2014) included aerogel as an option for retrofitting. As was the case with the VIP retrofitting option, the aerogel retrofitting option did not outperform the conventional materials. Another study from the UK investigated the CO_2 saving potential of retrofitting options with aerogel over the lifetime of a case study building (Dowson, 2012). This study looked into several options for aerogel applications in different building components in order to reach the intended energy performance. The study concluded that a parity between the CO_2 burden and CO_2 savings is achieved in less than 2 years, indicating that silica aerogel can provide a measurable environmental benefit but they study stated also that the "Results should be treated as a conservative estimate as the aerogel is produced in a laboratory, which has not been developed for mass manufacture or refined to reduce its environmental impact."

2.5 Summary of the state of the art of LCAs of SIM

From the collected information on LCA of SIM, Figure 2 illustrates the greenhouse gas (GHG) emissions of various types of insulation materials for A1-A3 modules (cradle-to-gate), where the functional unit was defined as 1 m^2 of the wall area of insulation with an identical thermal resistance (1 m^2K/W). The impact on GHG emissions was chosen based on the availability of the data. The data for conventional insulation materials were adopted from (Kono, Goto, Ostermeyer, Frischknecht, & Wallbaum, 2016).

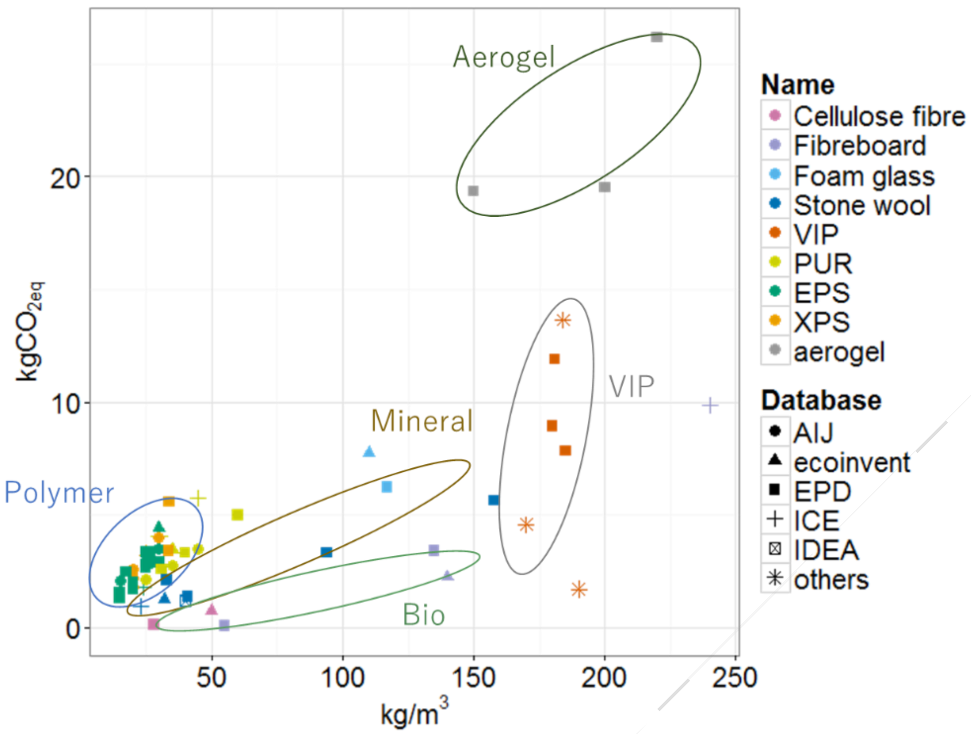

Figure 2. The mapping of GHG-emissions from various insulation materials with aligned thermal performance (identical thermal resistance (1 m^2K/W)) (n=57)

From the collected information, the competitiveness of VIP was higher than that of aerogel in terms of cradle-to-gate carbon emission. However, due to the lack of data for LCA on SIM today, a better representation of the environmental performance of the SIM is necessary. The subtask expects to contribute to the appropriate representation of the SIM as an outcome of the Annex 65.

2.6 Embodied energy

Embodied Energy (EE) is a common measure that quantifies the required energy to produce a certain product. The EE typically includes the energy consumed from extraction of the raw materials to the manufacturing of a product (Cradle-to-Factory gate), or to the end of life (Cradle-to-Grave). Today, EE is one of the most commonly applied lenses used on LCA studies, which is also adopted by Environmental Product Declarations (EPD) in EN 15804. Despite the frequent use of the method, as of February 2016, there seems to be no harmonized approach for EE. This harmonization is one of the topics that Annex 57 has worked on.

2.7 Life cycle cost calculation

Life Cycle Costing (LCC) adheres to life cycle thinking for quantifying the cost of a product or service. The method supports decision making beyond the costs of initial investment and takes into account costs associated with the operational phase and beyond. The result of LCC may differ depending on the time frame of the study. In the context of construction, ISO15686 (International Organization for Standardization, 2008) standardized the method for construction procurement.

In regards to SIM, the study from Dowson (2012) contains a section assessing the cost-effectiveness per ton of CO_2 saved over the lifetime of different measures to reduce the carbon emission of the investigated building, which includes aerogel options. The study concluded that ground floor insulation with aerogel is a highly cost-effective option. The study from (Alam, Singh, & Limbachiya, 2011) investigated the payback time of four material alternatives (glass fibre, foams, perlite and fibre/powder composites) on the achieved insulation performance with VIP and EPS in the UK. The payback time of installing EPS was less than a year for all cases while the payback time of installing VIP for all cases were more than 7 years when the value of space savings was disregarded. When the effect of space-saving was included, the case with VIP installation had a shorter payback time than that of EPS in the scenario with the highest insulating performance requirement.

3 Life cycle inventory of SIMs

3.1 Goal and scope of the LCA

The goal of the LCA conducted in this Annex was to obtain the up-to-date environmental impact of SIMs to support the decision-making of SIM users based on environmental information when applied in buildings. In addition, the analysis was also conducted to support SIM manufacturers to developing better environmental performing products. In order to achieve these goals, data for SIM manufacturing was collected. As the focus of the LCA was on revealing the environmental impact of SIMs, the system boundary of the LCA was cradle-to-gate, which is modules A1-A3 in EN 15804. The LCA was also conducted to allow hotspot identification of performance improvement of SIMs.

3.2 Covered SIMs

In the subtask, the data to create life cycle inventories (LCI) for SIMs were collected in order to allow transparent LCA of SIM applications. Due to confidentiality concerns as one of the major hindrances, production data from the participating manufacturers in the Annex could not be collected. Thus, the subtask pursued the creation of LCI based on secondary data. The covered LCI in this chapter would be: fumed silica VIP; aerogel blanket; and hollow silica nanosphere. The fumed silica VIP LCI was based on mass-produced data. The LCI data of aerogel blanket was considered to be on pilot-scale. Hence, large-scale production data will very likely result in lower environmental impacts. In the case of hollow silica nanosphere, the data was based on laboratory-scale which also implies an optimization potential for the production processes, e.g. on resource consumption during manufacturing.

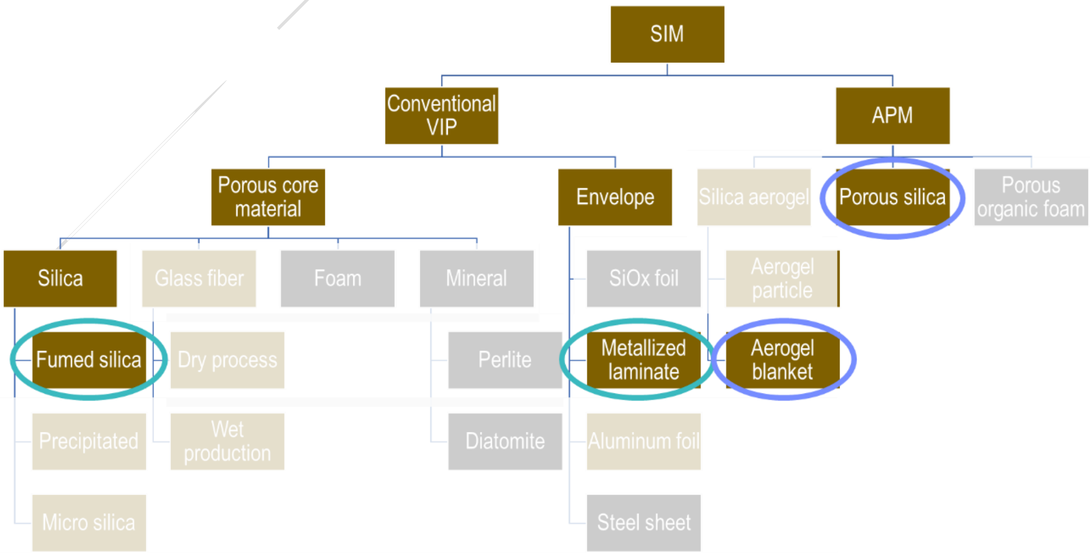

Figure 3. Overview of the covered SIM LCI in the study

The complete LCI datasets of each SIM are provided in Appendix A. All of the LCI datasets were created based on the ecoinvent database v3.2 (Wernet et al., 2016). The allocation rule of multi-output processes (Figure 4) was economic allocation which adheres to ecoinvent v3.2 (Wernet et al., 2016), and took recycled content approach for the allocation rule for multi-life cycle inventories. Multi-output processes (also called multi-functional processes) are a typical feature of many production systems. It describes the fact that the production system not only produces the primary product but other types of "by-products" as well. Some of the by-products can generate economic revenues but often to a much smaller extent than the "main" product.

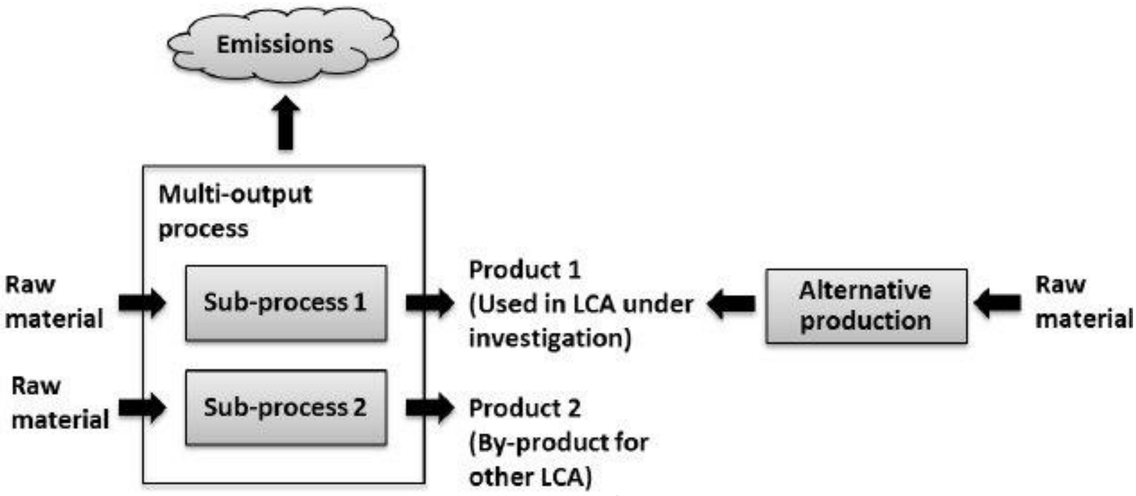

Figure 4. Overview of the allocation problem in multi-output processes (Messagie et al. 2013).

In LCAs, multi-output processes become a problem when it is not feasible to split a multi-output process into sub-processes connected to specific functions. The LCA practitioner needs to find a rationale for allocating the environmental load of the multi-functional process between its functions.

3.3 Background data and allocation

The study used ecoinvent v3.2 (Wernet et al., 2016) as the background data to construct the LCI of SIMs. The allocation approach that had been adopted for the multi-output process was the economic allocation and for the multi-life cycle process was the recycled content (cut-off) approach. In the LCA-terminology, cut-off is a understood as "Specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study." According to (ISO 2006).

3.4 LCI of Fumed silica VIP

In Figure 5, the flow chart of the created LCI of a fumed silica VIP is shown. The figure includes the detailed values of inventories, such as the quantities of the materials, mode of transportation and its distance, and the consumed energy. Full LCI of fumed silica VIP is given in Appendix A. The environmental impacts of each step are provided in chapter 4.1, Figure 8.

The represented LCI was approved by the participating fumed silica VIP manufacturers of the IEA Annex 65 as a representative fumed silica VIP dataset. However, the mix of the materials may slightly differ depending on the recipe of each manufacturer.

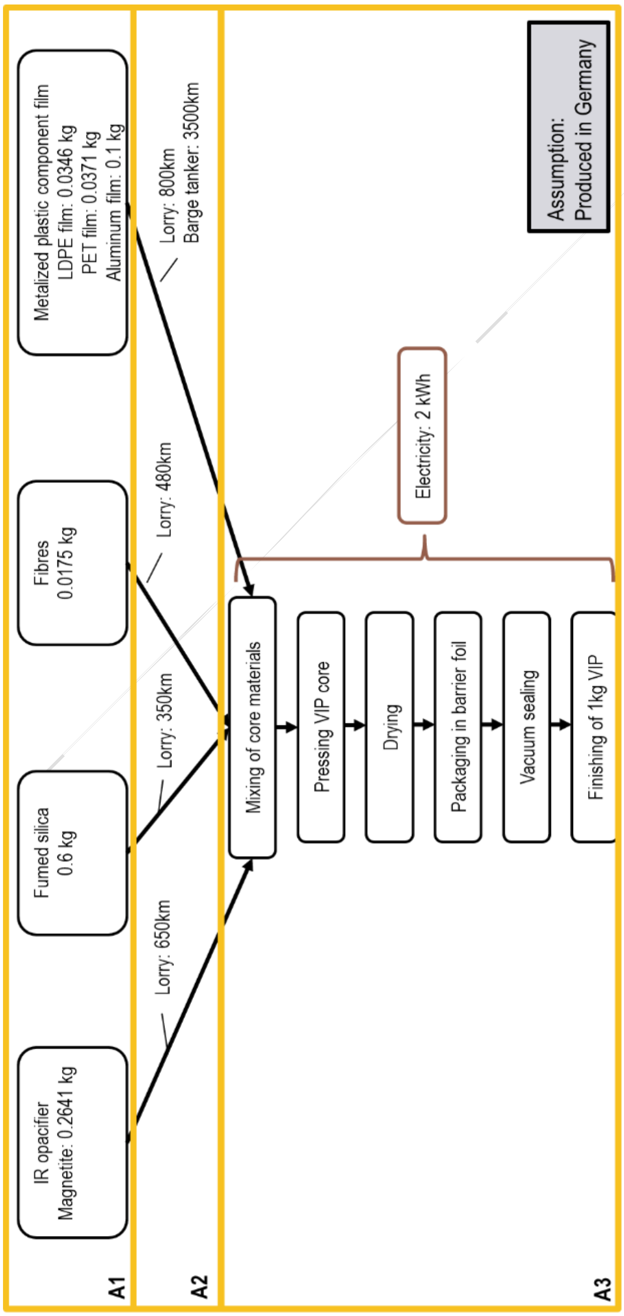

Figure 5. LCI flow chart of the fumed silica VIP (Karami et al., 2015)

The assumption that the fumed silica VIP is produced in Germany affects the environmental impact of the product as the average emission factors for 1 kWh of the German electricity production mix has been applied for the analysis. This implies that a production of the same fumed silica VIP in Sweden would very likely lead to lower greenhouse gas emissions due to an electricity mix that steems mainly from water and nuclear power as well as wind energy, which are less greenhouse gas-intensive as the German electricity mix that still contains a lot of coal as primary energy carrier. On the other side, the production of fumed silica VIP in Poland would lead to much higher Greenhouse gas emissions due to the high load of coal as primary energy source.

3.5 LCI of Aerogel blanket

In Figure 6, the flow chart of an aerogel blanket LCI dataset is represented. As with the VIP case, the figure includes the detailed values of each inventory. The figure includes the representation of two drying methods, which are ambient and supercritical drying. Full LCI of aerogel is given in Appendix A. The environmental impacts of each step are provided in chapter 4.2, Figure 9.

As the LCI data is based on a pilot-scale it gives an indication that at a full-scale production, lower input values are to be expected which would lead to lower environmental impacts.

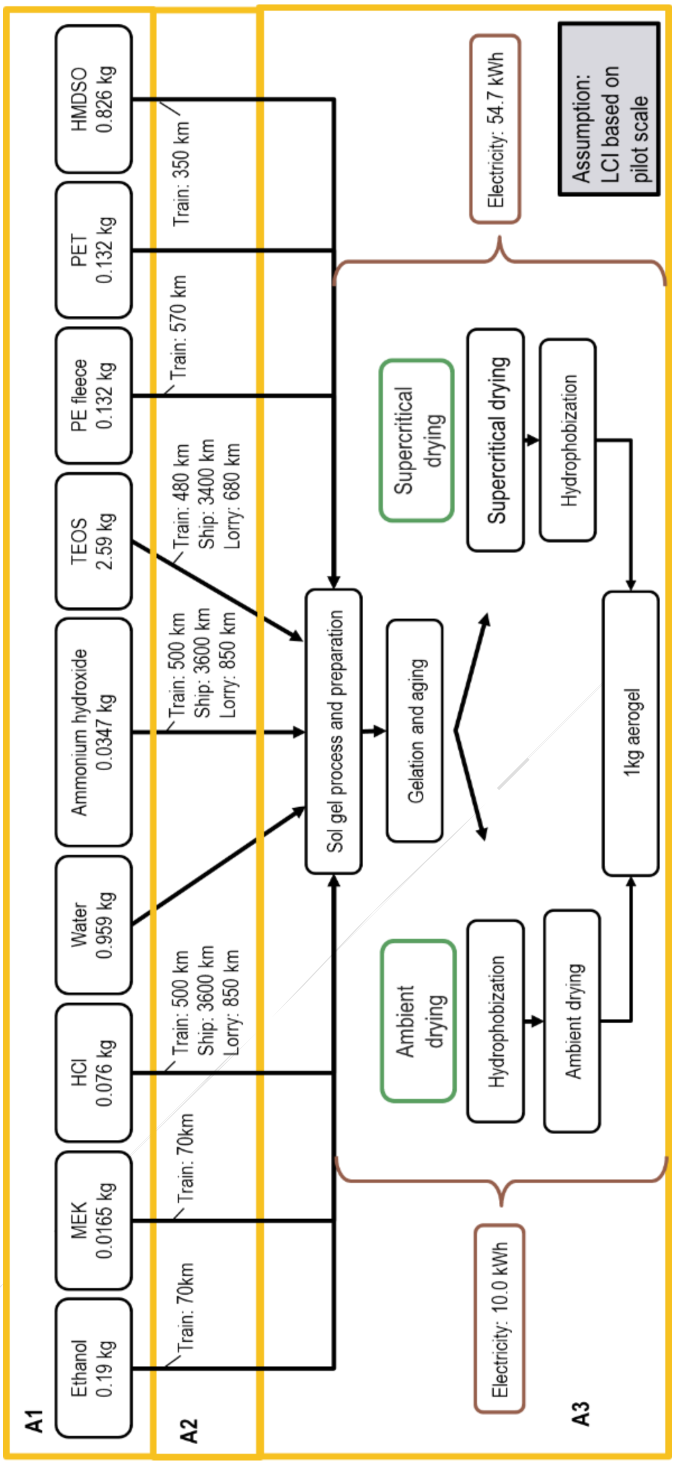

Figure 6. LCI flow chart of aerogel blanket (Kasser U., Frischknecht R., Klingler M., Savi D., Stolz P., Tschümperlin L., Wyss F., Itten, 2016)

From the received feedback and discussion with the manufacturers and the experts in the IEA Annex 65, the LCI datasets are considered to represent pilot scale manufacturing of the aerogel blankets.

3.6 LCI of Hollow silica nanosphere

As the last type of SIM which LCI dataset was available, a hollow silica nanosphere was identified. In Figure 7, the laboratory based data of LCI and its flow has been shown. Full LCI of hollow silica nanosphere is given in the Appendix. The environmental impacts of each step are provided in chapter 4.3, Figure 10.

As the LCI data is based on a laboratory-scale the environmental impacts on a full-scale production can differ significantly.

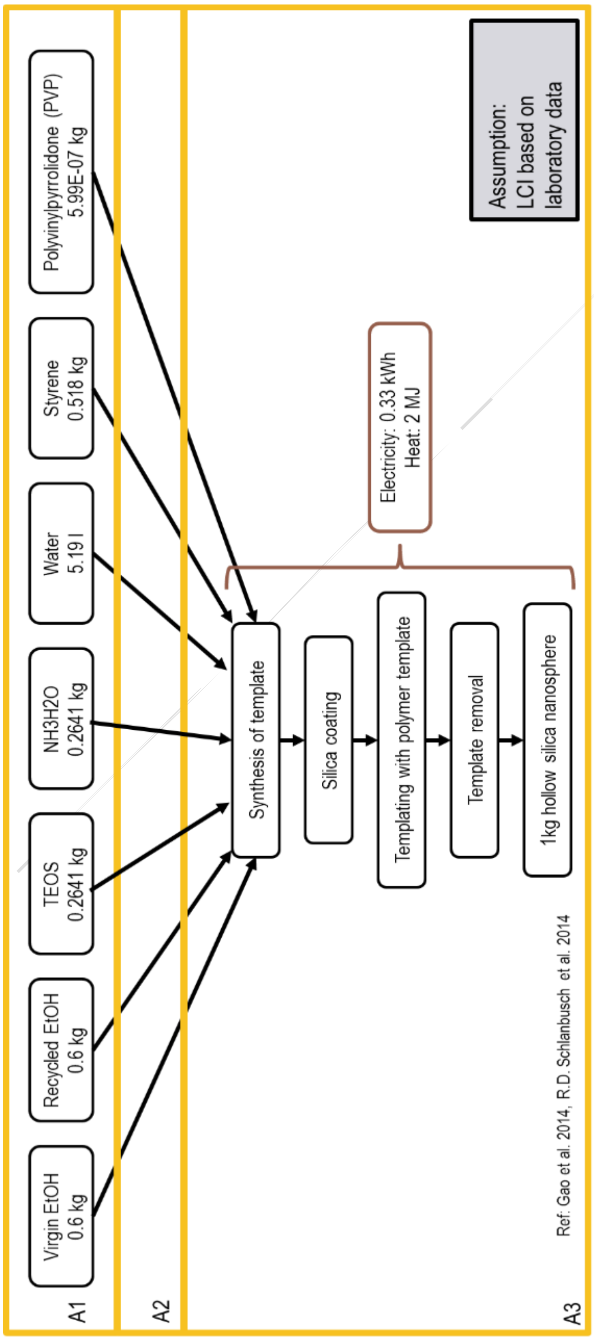

Figure 7. LCI flow chart of hollow silica nanosphere (Gao, Sandberg, & Jelle, 2014; Schlanbusch, Jelle, Christie Sandberg, Fufa, & Gao, 2014)

4 Life cycle impact assessment of the SIMs

This section shows the results of life-cycle impact assessment (LCIA) using the data on the highest impact processes for the SIMs from a climate change point-of-view; the hotspots. The impacts were assessed based on the emitted Greenhouse gas which was quantified through the global warming potential (GWP) defined in (IPCC, 2013). In order to judge the environmental performance of the SIMs when applied in buildings, the impact was assessed and compared with conventional insulation materials by the GHG emissions. It has to be noted that better data for conventional insulation materials were available when conducting an LCIA thanks to its common use.

4.1 Fumed silica VIP

Figure 8 shows the result of a contribution analysis that quantifies the relative contribution of each input parameter (Zampori et al. 2016) of the LCIA of a VIP with fumed silica. The core material of the VIP, the fumed silica, has a dominating impact on its GHG emissions according to (IPCC, 2013). For fumed silica VIPs to improve their environmental performance, measures to reduce the GHG emissions generated during the manufacturing of the core material are essential. However, with the current profile of fumed silica VIP's improvement potential of its performance through process optimization is rather limited as the largest share of the environmental impacts stems from the fumed silica itself and not the other processes, such as transportation, packaging etc.

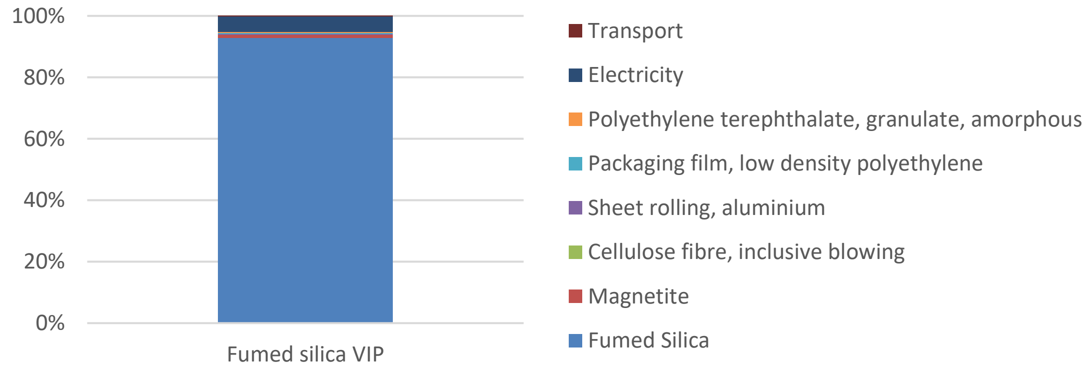

Figure 8. The result of the composition analysis of cradle-to-gate LCIA of fumed silica VIP in GWP IPCC2013 100a (IPCC, 2013)

4.2 Aerogel blanket

Figure 9 shows the contribution analysis of the pilot-scale aerogel with two different manufacturing procedures. For the ambient dried aerogel, the impact of the material used is dominant, representing more than 60% of the impact. While the impact of electricity contributes 30% of the ambient dried aerogel embodied energy, it is responsible for 80% of the aerogel made by supercritical drying. This highlights the significant improvement potential of the environmental performance of aerogel made by supercritical drying, for instance by sourcing the electricity from renewable energies.

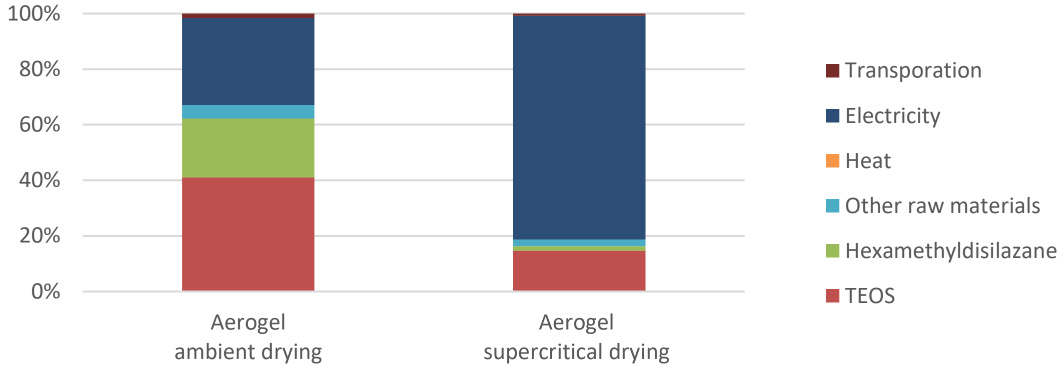

Figure 9. The result of the composition analysis of cradle-to-gate LCIA of ambient drying and supercritical drying aerogel blanket in GWP IPCC2013 100a (IPCC, 2013)

4.3 Hollow silica nanosphere

The result of the contribution analysis of the lab-scale hollow silica nanosphere is shown in Figure 10. It shows the domination of the environmental impact by silica coating. For the improvement of the environmental performance of the hollow silica nanosphere, further improvement on silica coating would be necessary. Obviously the upscaling from the lab-scale to the production-scale allows for some improvement, which cannot be assessed at the moment.

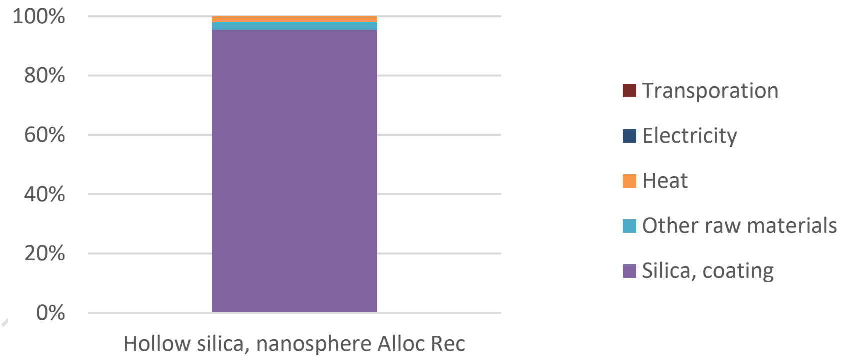

Figure 10. The result of the composition analysis of cradle-to-gate LCIA of hollow silica nanosphere in GWP IPCC2013 100a (IPCC, 2013)

4.4 Summary of LCIA results

Figure 11 summarises embodied carbon emission of insulation materials with the SIM LCIs created for this report. They represent a Cradle to Factory analysis (A1-A3 of EN15804) covering the module A1-A3 of EN15804. Figure 11 is an update of Figure 2 by adding additional information from the new version of ecoinvent database and the created LCI of the SIMs. The included SIM data were fumed silica VIP with two allocation methods (mass-based and economic) and aerogels produced with ambient and kiln drying. The result of hollow silica nanosphere has been excluded as the available LCI data of the material was laboratory-based where others were at least representing the pilot-scale LCI data.

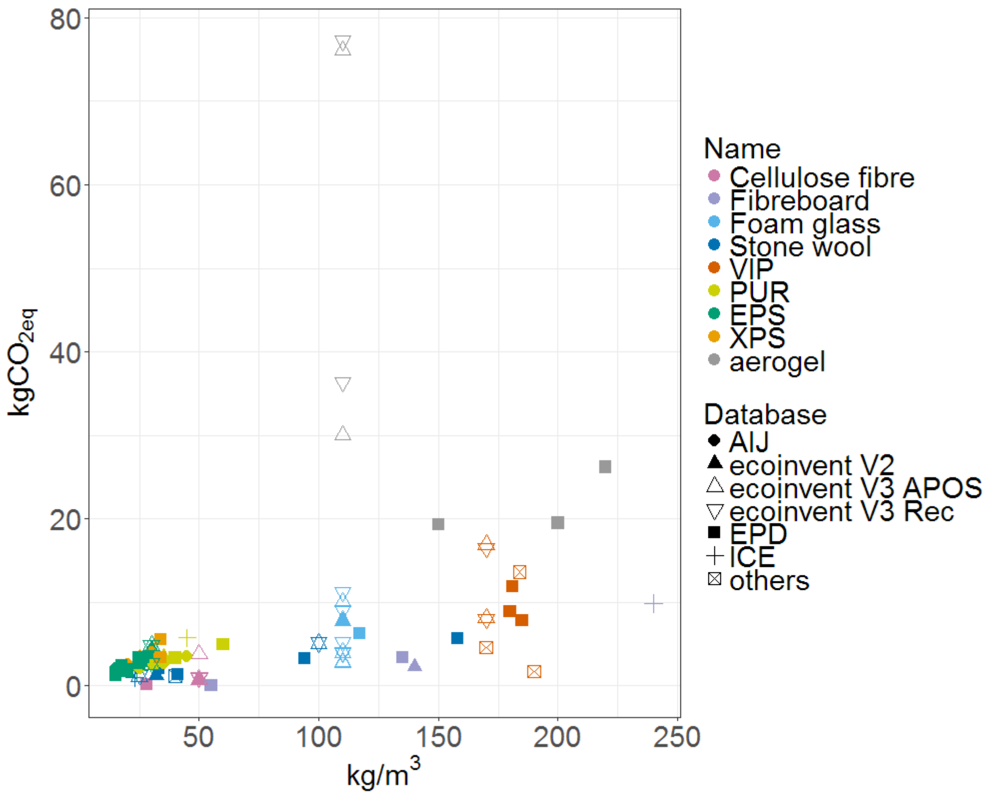

Figure 11. The updated mapping of GHG emission from various insulation materials with aligned thermal performance (n=91)

The LCIA result of fumed silica VIPs with a mass-based allocation is in relatively good accordance with the values of published EPDs, which was less than 10kg CO_2eq. Meanwhile, the result with an economic-based allocation showed higher values than any of the published EPD results. The fact suggests that the representation of the LCI collected in the subtask properly represents the products in the market when the impact is calculated by mass based allocation. This fumed silica, the hotspot for the embodied emission of fumed silica VIPs is created via a multi-output process together with Hydrochloric Acid (HCl). While HCl is rather a ubiquitous chemical for various applications, fumed silica is considered more of a value-added chemical which tends to have higher economic value. With such a difference, the environmental impacts of such multi-output process-based products being allocated based on mass could be questionable. Nonetheless, the LCI result from the subtask allows such considerations to take place transparently and allows fair comparison among different product categories with differences in assumptions. This allows conducting sensitivity analysis for various assumptions that would not be possible for the existing EPDs that do not disclose all inputs and production steps.

Meanwhile, the LCIA result of aerogels had quite a deviation from the published EPD values for the created LCI for both of the drying methods. This is due to the fact that the best LCI data collected during the IEA Annex 65 represented pilot scale data. The data has been collected from different sources, such as existing literature and interviews as well as review processes with participants from the Annex based on provided LCI datasets. Thus, the collected LCI may not be appropriate to be used to compare with other insulation materials as the aerogels may not be appropriately represented. However, the hotspot analysis provides a good basis for potential improvement opportunities for the aerogels environmental performance, such as producing in a country with a more carbon-friendly electricity grid mix, such as France or Sweden.

5 Case studies on LCA and LCC

5.1 Case 1: Hypothetical case building for 2 retrofitting options

Based on the created LCI datasets and the LCIA results, a case study of a building retrofitting was made for calculating the economic and environmental payback time. For the calculation, the equations used in the study from (Alam et al., 2011; Alam, Singh, Suresh, & Redpath, 2017), which calculated both of the payback times based on the energy demand of buildings, was adopted. The study assumed applying insulation materials in the interior wall. The payback time of the renovation options for four northern European cities was investigated, which reflects the regional condition differences such as fuel costs, heating degree days and the land price.

In Table 3, the details of SIMs used for the case study is shown. For the embodied emission of the fumed silica VIP, the value with economic allocation has been used to show conservative results.

	Fumed silica VIP	Aerogel Ambient drying	Aerogel Supercritical drying
Density [kg/m^3]	170	150	150
Thermal conductivity [W/mK]	0.0035	0.015	0.015
Price [EUR/m^3]	2755	3000	3000
kgCO_2eq/kg	28.45	19.52	49.42

Table 3. Specification of the SIMs for case studies

5.1.1 Case description

The building used to calculate the economic and CO_2 payback time was considered to have the following dimension and specifics.

- Size of the building: 15m x 15m x 6m (2 stories high)
- Initial U-value of envelope system: 2.1 W/m^{2}K
- U-value after renovation: 0.3 W/m^{2}K
- Gas is used for heating

When calculating the economic payback time, the gain from increased room space has been taken into account. For such purpose, a case with EPS was taken as a benchmark for calculating the increased room space. In Table 4, the required thickness of the insulation materials to achieve the target U-value is given.

	unit	wall
EPS	mm	95
Fumed silica VIP	mm	23
Aerogel	mm	54

Table 4. Thickness of applied insulation materials for retrofitting an interior wall

As mentioned above, the retrofit assumed to take place in four Northern European cities where the heating demand could be seen as the dominating part of the heating ventilation and cooling (HVAC) of the buildings. The four cities considered were London, Zurich, Berlin and Gothenburg. In Table 5, the data used for this case study is shown.

	London	Berlin	Zurich	Gothenburg
HDD [C day/yr] [2]	1624	2433	2446	3186
Monthly rent [EUR/m^2]	117[3]	9[4]	73[5]	10[6]
Gas price [EUR/m^3][7,8]	0.71	0.75	0.95	1.17

Table 5. Regional conditions for calculating economic and carbon payback time

5.1.2 Payback time calculation method

For calculating the saved energy after the retrofitting, Eq. 1 was used.

$$\text{annual saved energy} = 24 \times \text{HDD} \times \text{A}_{\text{surf}} \times \Delta\text{U} \qquad \text{Eq. 1}$$

where,

- HDD: heating degree days [Kd/a]
- A_{surf}: Insulated surface area [m^2]
- ΔU: changes in thermal transmittance [W/m^2K]

Based on the calculated saved energy, the payback time was calculated as the following.

$$\text{Payback time} = \frac{\text{Total expense/emission}}{\text{Annual gain}} \qquad \text{Eq. 2}$$

where,

- Total expense = cost for installed SIM
- Total emission = embodied emission of SIM
- Annual economic gain = rent increase from the increased land + saved energy cost
- Annual environmental gain = saved emission from energy consumption

For calculating the saved cost and emission from gas consumption, the following values in Table 6 have been used. The emission factor was taken from ecoinvent (Wernet et al., 2016), and other values were from (Alam et al., 2011).

[2] The data of heating degree days were collected at www.degreedays.net
[3] Based on the market price as 100GBP/ft^2a
[4] Based on the price shown in http://www.berlinhyp.de/uploads/media/WMR_2016_EN_WWW_20160111.pdf
[5] Based on the market price of a dwelling with 2400CHF for 30m^2
[6] Based on the price shown in http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BO__BO0406__BO0406E/BO0406Tab02/table/tableViewLayout1/?rxid=c2a456a3-8793-494c-a3fb-bc2fbe895215
[7] Gas price data for London is based on the (Alam et al., 2011)
[8] Gas price data of the cities except London is based on the prices indicated in the Eurostats: http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Electricity_and_gas_prices,_second_half_of_year,_2013%E2%80%9315_(EUR_per_kWh)_YB16.png

Parameters	Unit	Value
Emission factor of natural gas	[kgCO_2eq/kWh]	0.1837
Heating value of natural gas	MJ/m^3	39.5
Efficiency of heating system	%	90

Table 6. Parameters used for calculating the saved gas from the retrofitting

5.1.3 Results of payback time

Table 7 shows the result of the calculated payback times for the four investigated cities in northern Europe.

	SIMs	Economic payback time [years]	CO_2 payback time [years]
London	VIP	3.7	8.6
	Amb aerogel	13.8	12.3
	SC aerogel	13.8	31.2
Berlin	VIP	7.0	5.7
	Amb aerogel	19.1	8.2
	SC aerogel	19.1	20.8
Zurich	VIP	3.3	5.7
	Amb aerogel	12.5	8.2
	SC aerogel	12.5	20.7
Gothenburg	VIP	3.5	4.4
	Amb aerogel	8.6	6.3
	SC aerogel	8.6	15.9

Table 7. Summary of resulting payback times for the investigated cities

The result of the economic payback time for fumed silica VIP suggests that cities with high renting price or high heating demand and gas price can have around 4 years of payback time. Meanwhile, the economic payback time of aerogels was longer than 10 years except in Gothenburg. This is due to the rather thick layer being applied on the wall, which may call for an optimization based on the cost and the thermal insulation performance.

The payback time of CO_2 was less than 5 years for VIP in Gothenburg, where the highest heating demand was seen. Since the case study took the embodied emission of VIP with economic allocation, the payback time calculated with the embodied emission of it with mass-based allocation could result in shorter time. For the ambient dried aerogel, the CO_2 payback time was less than 9 years except in London where the heating demand is the minimum. Since the embodied emission of the aerogel represents the LCI from pilot-scale production and the deviation between the values from published EPDs are large, the payback time for marketed products can be expected to be shorter than the results shown in this study. Nonetheless, the finding suggests that with proper consideration of where and how to application of the aerogels takes place, the performance of the material could be highly valued.

5.2 Case 2: Real case buildings with special boundary conditions

In this section, a few existing cases where SIMs were applied due to various limitations are introduced.

5.2.1 Case of a traditional house renovation in Thun, Switzerland

A traditional swiss house in Thun needed a renovation to meet the latest thermal insulation standards while maintaining its architectural features. With the limitation on the degree of freedom for the renovation option, VIP was used to meet the challenge. The VIP was applied on the roof, balcony and the external wall, fulfilling the requirement of preserving the aesthetics as well as the insulation performance. "For the insulation of the roof one layer of 25 mm thick panels plus 60 mm wooden fireboard was used. The existing downspout and roof tiles were perfectly reusable for the new insulated roof. The wall adjacent to the balcony was covered with two layers of 20 mm thick panels and one layer of 20 mm wooden fireboard. The vacuum insulation panels contribute to an aged thermal conductivity of 0.0061 W/m*K." [9] With the traditional insulation materials, neither the performance nor the architectural design requirement would have been met.

Figure 12. A picture of the renovated traditional swiss house in Thun, Switzerland[10]

[9] VIPA International Case Study VIP technology offers maximum energy efficiency, while retaining the architecture of a traditional Swiss house. Retrieved May 23, 2017, from http://vipa-international.com/uploads/kcFinder/files/VIPA Case Study - Microtherm.pdf

[10] VIPA International Case Study VIP technology offers maximum energy efficiency, while retaining the architecture of a traditional Swiss house. Retrieved May 23, 2017, from http://vipa-international.com/uploads/kcFinder/files/VIPA Case Study - Microtherm.pdf

5.2.2 Case of a renovation of a school building to meet passive house standard in Freilassing, Germany

In 2011, the first-ever project of a school renovation to a passive house standard was carried out[11]. For such a project, VIPs were used to save as much space as possible while meeting the energy requirement from the standard. The value of VIPs was specially recognized by the fact that the VIPs achieved high insulating performance without compromising the room height.

Figure 13. A picture of the renovated school building in Freilassing, Germany (Porextherm, 2012)

5.2.3 Case of an office building renovation in Rheinfelden, Switzerland

In 2015, renovation of an office building in Rheinfelden, Switzerland has been made which used CALOSTAT® and VIP (Evonik Resource Efficiency GmbH, 2016). The renovation increased the insulation performance of the building which the façade U-value improved to 0.18 W/m^{2}K or below. This performance improvement of the façade is expected to reduce the energy consumption of the building by 143 MWh per year. From this saved energy consumption from the operational phase (B6 module in EN 15804) of the building, 28.9 tCO$_2$eq of the GHG reduction from the corresponding phase is expected.

Figure 14. A picture of the renovated office building in Rheinfelden, Switzerland (Evonik Resource Efficiency GmbH, 2016)

[11] VIPA International Case Study VIP technology helps turn '70s secondary school into state of the art passive house. Retrieved May 23, 2017, from http://vipa-international.com/uploads/kcFinder/files/VIPA%20International%20Case%20Study%20-%20Porextherm.pdf

6 Conclusion on SIM LCA

Several previous studies which have dealt the LCA of SIMs, although most of them were lacking the details of LCI which would be necessary for a transparent comparison of different types of insulation materials. This subtask constructed such transparent LCI through cooperation with manufacturers although this was a challenge due to various aspects including the confidentiality issues. This led the subtask to develop the LCI mainly based on the existing publications with various feedback opportunities by the Annex participants.

The LCIA result of the LCI of VIP showed a good level of coherency with the published EPDs, which normally do not contain fully transparent LCI information. The result creates a solid basis for comparison with the conventional insulation materials for other LCIA studies.

Meanwhile, the LCIA result of the created aerogel LCI showed a large difference between the published EPDs. This was presumed to be due to the fact that the available LCI information only represented pilot scale. Although EPDs represent product-specific LCIA results, the level of information described in this document may not always be sufficient to allow a fair comparison. This lack of transparency remains a challenge for the new advanced materials.

A hypothetical case of renovation which looked into the economic and the environmental payback time showed SIMs have very high simple payback times in most of the northern European cities. However, places with high land price or high heating demand can affect the competitiveness of the SIMs, both economically and environmentally. In reality, there are various limitations that may affect the decision of insulation material selection. Cases where space limitations are given or preservation of the architectural design was seen as the reasons for implementing the SIMs in the existing building renovation projects.

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Appendix A.

<table>
<tr><th></th><th></th><th>Value</th><th>Unit</th><th>Comment</th></tr>
<tr><td>Output</td><td>VIP (mass) {DE}| production| Alloc Rec, U</td><td>1</td><td>kg</td><td></td></tr>
<tr><td>Input</td><td>Fumed Silica (mass) {DE}| Production| Alloc Rec, U</td><td>0.5984</td><td>kg</td><td></td></tr>
<tr><td></td><td>Magnetite {GLO}| market for | Alloc Rec, U</td><td>0.2641</td><td>kg</td><td>IR Opacifier</td></tr>
<tr><td></td><td>Cellulose fibre, inclusive blowing in {CH}| production | Alloc Rec, U</td><td>0.0175</td><td>kg</td><td></td></tr>
<tr><td></td><td>Sheet rolling, aluminium {GLO}| market for | Alloc Rec, U</td><td>0.1</td><td>kg</td><td></td></tr>
<tr><td></td><td>Packaging film, low density polyethylene {RER}| production | Alloc Rec, U</td><td>0.0346</td><td>kg</td><td></td></tr>
<tr><td></td><td>Polyethylene terephthalate, granulate, amorphous {RER}| production | Alloc Rec, U</td><td>0.0371</td><td>kg</td><td></td></tr>
<tr><td></td><td>Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Rec, U</td><td>0.2094</td><td>tkm</td><td>350km</td></tr>
<tr><td></td><td>Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Rec, U</td><td>0.1717</td><td>tkm</td><td>650km</td></tr>
<tr><td></td><td>Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Rec, U</td><td>0.0084</td><td>tkm</td><td>480km</td></tr>
<tr><td></td><td>Transport, freight, inland waterways, barge tanker {RER}| processing | Alloc Rec, U</td><td>0.2511</td><td>tkm</td><td>3500km</td></tr>
<tr><td></td><td>Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Alloc Rec, U</td><td>0.0574</td><td>tkm</td><td>800km</td></tr>
<tr><td></td><td>Electricity, medium voltage {DE}| market for | Alloc Rec, U</td><td>1</td><td>kWh</td><td></td></tr>
<tr><td></td><td>Electricity, high voltage {CH}| natural gas, import from Germany | Alloc Rec, U</td><td>1</td><td>kWh</td><td></td></tr>
</table>

Table 8. LCI of fumed silica VIP

		Value	Unit	Comment
Output	Aerogel, ambient drying {CH}| Market | Alloc Rec, U	1	kg	
Input	TEOS {US}| production | Alloc Rec, U	2.59	kg	
	Ethanol, without water, in 99.7% solution state, from fermentation {Europe without Switzerland}| dewatering of etl	0.19	kg	
	Tap water {Europe without Switzerland}| market for | Alloc Rec, U	0.959	kg	
	Hydrochloric acid, without water, in 30% solution state {CA-QC}| hydrochloric acid production, from the reaction of I	0.076	kg	
	Methyl ethyl ketone {RER}| production | Alloc Rec, U	0.0165	kg	
	Ammonium hydroxide {US}| production | Alloc Rec, U	0.0347	kg	
	Hexamethyldisilazane {GLO}| amination of chlorosilane | Alloc Rec, U	0.826	kg	
	Polyethylene terephthalate, granulate, amorphous {RER}| production | Alloc Rec, U	0.132	kg	
	Fleece, polyethylene {RER}| production | Alloc Rec, U	0.132	kg	
	Chemical factory, organics {RER}| construction | Alloc Rec, U	4E-10	p	
	Transport, freight, sea, transoceanic tanker {GLO}| processing | Alloc Rec, U	14.2	tkm	
	Transport, freight train {Europe without Switzerland}| electricity | Alloc Rec, U	1.57	tkm	
	Transport, freight, lorry, unspecified {GLO}| market for | Alloc Rec, U	2.35	tkm	
	Electricity, medium voltage {RFC}| market for | Alloc Rec, U	10	kWh	

Table 9. LCI of aerogel blanket with ambient drying in pilot scale

<table>
<tr><th></th><th></th><th>Value</th><th>Unit</th><th>Comment</th></tr>
<tr><td>Output</td><td>Aerogel, supercritical drying {CH}| Market | Alloc Rec, U</td><td>1</td><td>kg</td><td></td></tr>
<tr><td>Input</td><td>TEOS {US}| production | Alloc Rec, U</td><td>1.97</td><td>kg</td><td></td></tr>
<tr><td></td><td>Ethanol, without water, in 99.7% solution state, from fermentation {Europe without Switzerland}| dewatering of et</td><td>0.047</td><td>kg</td><td></td></tr>
<tr><td></td><td>Tap water {Europe without Switzerland}| market for | Alloc Rec, U</td><td>1.11</td><td>kg</td><td></td></tr>
<tr><td></td><td>Hydrochloric acid, without water, in 30% solution state {CA-QC}| hydrochloric acid production, from the reaction of</td><td>0.0303</td><td>kg</td><td></td></tr>
<tr><td></td><td>Methyl ethyl ketone {RER}| production | Alloc Rec, U</td><td>0.0636</td><td>kg</td><td></td></tr>
<tr><td></td><td>Isopropanol {RER}| production | Alloc Rec, U</td><td>0.0212</td><td>kg</td><td></td></tr>
<tr><td></td><td>Ammonium hydroxide {US}| production | Alloc Rec, U</td><td>0.218</td><td>kg</td><td></td></tr>
<tr><td></td><td>Hexamethyldisilazane {GLO}| amination of chlorosilane | Alloc Rec, U</td><td>0.136</td><td>kg</td><td></td></tr>
<tr><td></td><td>Water, completely softened, from decarbonised water, at user {RER}| production | Alloc Rec, U</td><td>0.0909</td><td>kg</td><td></td></tr>
<tr><td></td><td>Polyethylene terephthalate, granulate, amorphous {RER}| production | Alloc Rec, U</td><td>0.136</td><td>kg</td><td></td></tr>
<tr><td></td><td>Fleece, polyethylene {RER}| production | Alloc Rec, U</td><td>0.136</td><td>kg</td><td></td></tr>
<tr><td></td><td>Carbon dioxide, liquid {RER}| market for | Alloc Rec, U</td><td>0</td><td>kg</td><td></td></tr>
<tr><td></td><td>Chemical factory, organics {RER}| construction | Alloc Rec, U</td><td>4E-10</td><td>p</td><td></td></tr>
<tr><td></td><td>Transport, freight, sea, transoceanic tanker {GLO}| processing | Alloc Rec, U</td><td>13.1</td><td>tkm</td><td></td></tr>
<tr><td></td><td>Transport, freight train {Europe without Switzerland}| electricity | Alloc Rec, U</td><td>1.19</td><td>tkm</td><td></td></tr>
<tr><td></td><td>Transport, freight, lorry, unspecified {GLO}| market for | Alloc Rec, U</td><td>2.05</td><td>tkm</td><td></td></tr>
<tr><td></td><td>Electricity, medium voltage {RFC}| market for | Alloc Rec, U</td><td>54.7</td><td>kWh</td><td></td></tr>
</table>

Table 10. LCI of aerogel blanket with supercritical drying in pilot scale

		Value	Unit	Comment
Output	Hollow silica nanosphere {NO}| production| Alloc Rec, U	1	kg	
Input	Silica, coating {NO}| production| Alloc Rec, U	1	kg	
	Polystyrene nanospheres template {NO}| Production| Alloc Rec, U	5.7	kg	
	Heat, from styrene combustion {NO}| production| Alloc Rec, U	0.54	kg	
	Chemical factory {RER}| construction | Alloc Rec, U	4E-10	kg	
	Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natur	2	MJ	
	Electricity, medium voltage {NO}| market for | Alloc Rec, U	0.333	kWh	

Table 11. LCI of hollow silica nanosphere in lab scale

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