Innovative insulation materials - specific issues performing LCA in early development phases

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Abstract

Facing climate change, ecological sustainability forms an important task of recent research, which is scientifically evaluated with life cycle assessments (LCAs). Heating purposes in residential sectors cause substantial amounts of CO_2 emissions. Therefore, sustainable insulation material development is essential, whereby aerogels are an attractive substitute with low thermal conductivities. The HOMESKIN project aimed to develop an aerogel-based insulation material that achieves minor environmental impacts by material recycling and efficient manufacturing [**1**]. The LCA is conducted with GaBi in accordance with EN ISO 14040/14044. However, performing LCA in this state of research has proved difficulties. Therefore, in this study, impacts are investigated on how uncertainties due to missing data and resultant assumptions contribute to deviations in results. For generating LCAs, detecting high energy processes is essential as well as materials with significant environmental impacts. This information considers confidential data and is often not completely accessible, especially for innovative products. Besides, aerogels are produced with chemicals whose economic data are extremely rare or might be outdated. Assumed values could cause uncertainties that are difficult to predict. Furthermore, scale-up scenarios create additional uncertainties. The study demonstrates that environmental impacts in early development stages can hardly be assessed – which indicates that LCA generates pessimistic or too optimistic results.

Keywords: Life cycle assessment, sustainability, insulation material, aerogel-based, development stage.

Introduction

Facing global resource consumption and climate change, sustainability forms an important task of recent research, whereby the ecological part can be scientifically evaluated with Life cycle assessments (LCAs).

According to the report of the Intergovernmental Panel on Climate Change from 2013 [**2**], a constant increase of greenhouse gas emissions will to a mean temperature increase from 2.6 up to 4.8 kelvin by 2100. Consequences are, among other things, melting of polar caps, sea-level rise and higher frequency of extreme weather events. Emitted carbon dioxide emissions from the energy provision sector are one of the main causes for the human-induced climate change. Currently, approximately 32 % of global final energy demand and 19 % of global greenhouse gas emissions are allocated to the building sector [**2**]. Heating purposes in residential sectors having a significant share in the total global energy demand also cause substantial amounts of carbon dioxide (CO_2) emissions. For this reason, ecological sustainability requires innovative insulation materials with the focus on resource reduction and an increase in energy efficiency. For minimizing heating requirements, more efficient and sustainable insulation materials are essential. At this point, thoroughly investigated nanostructured insulation materials like silica aerogels are presented as an attractive substitute as insulation material for buildings [**3, 4**] because of its very low thermal conductivities with approximately ranging from 0.017 W/mK to 0.021 W/mK [**5**].

Challenges for these products with regard to ecological aspects are the high production effort of the pre-products and of the aerogel itself [**6,7**]. The HOMESKIN project aimed to develop a new silica aerogel-based insulation material composite that achieves minor environmental impacts by recycling raw materials and by an improved efficient manufacturing [**1**]. The production is currently laboratory-scaled. To assess ecologically the current and future potential of products, LCA represents an important tool. However, the LCA performance of HOMESKINs silica aerogel-based composite proved to be difficult. The reasons for this are the rare data availability of raw materials and uncertainties concerning the further production development. Hetherington et al. describes in [**8**] the uncertainties of LCAs in early development stages as critical ones. Nevertheless, they highlight that studies of

LCAs for products of early development stages are important and advantageous as they lead to an improved understanding and development of such LCA studies. Though, LCA studies of silica aerogel based products are rarely published [**9**].

There are several issues concerning life cycle assessment in the early stages of scientific supervision during the development phase of new products. Firstly, the quality of impact assessments depends initially on data completeness and precise inventory analyses concerning material recipe, energy use and product manufacturing conditions. It is essential to detect those unit processes that cause particularly high energy consumption and primary materials with significant environmental impacts in the early stage of product development as well. This information generally comprises highly sensitive or confidential data and is therefore often not completely accessible. This is especially the case if innovative products are under investigation. This also affects necessary pre-products and raw materials. Aerogels are produced on the basis of chemicals for which ecological data is extremely rare to find, partly outdated or even unavailable [**7, 9 and 10**]. Missing information has to be assumed though, which causes uncertainties. Furthermore, future production scenarios may strongly differ from the laboratory scale systems that are used in the early phase of product development. To assess the future environmental potential of the production, considering further development of the production conditions is essential. This requires assumptions that are difficult to predict but can strongly influence the results.

Thus the goal and scope of LCAs of the described type is mainly focused on estimations concerning a still existing variety of choices during the early stage of a product development rather than evaluation of the product itself. The central question should not be “is this product better than its competitors?” but “is there a true chance to realize a significant improvement in comparison with competitors?” instead. The latter question can only be answered considering different scenarios or with use of interval arithmetic to cover a potentially broad range of alternatives in a single calculation.

Therefore, this study concentrates on problems of LCA in early research phase through the example of HOMESKINS lab-scale produced aerogel-based insulation material and possible discrepancies between current and future manufacturing. The exemplary results presented in the following chapters are based on the scenario approach.

Experimental

Silica-aerogel based insulation materials

Silica aerogels are three-dimensional networks whose skeleton is based on silica. The share of air-filled gaps within the structure is 80 to 99.8 % [**5, 11**]. Therefore, aerogels are highly porous materials with densities between 0.004 g/cm³ and 0.5 g/cm³ [**5**]. The average pore diameter is with 20 nm to 40 nm lower than the mean free path length of gas particles with 68 nm in diameter and with normal ambient pressure [**11**]. This prevents thermal conduction in the pores and contributes to low thermal conductivities, and is thus suitable and very interesting for building sector as insulation material [**3**]. Mainly for such applications, composite insulation materials are developed with support structures like foils, fleeces or woven material [**4**].

For the first time in the 1930s the production of an aerogel was succeeded but used to take a long time. [**12**]. Hence, research and material development was only intensified after developing a faster production process named sol-gel-process in the 1960s [**5, 12**]. With the sol-gel process, the aerogel is produced in four steps: the sol production, its gelation, aging of the gel and last gel drying. The sol is a dispersion produced with precursors like tetraethyl orthosilicate (TEOS). The sol is converted to a gel through chemical synthesis and solvents like ethanol, catalysts and water. After gelation, the pores of the gel are still filled with sol that can bond chemically with the gel structure through condensation. For that reason, the aging step is important in order to achieve higher gel structure rigidity. At the end of the reaction, the liquid is removed during the drying step. Thereby, subcritical drying is discussed as method economic potential [**4**]. The drying procedure risks destroying the fragile gel structure, though. The capillary forces caused by evaporation of the liquid results in significant shrinkages and irreversible changes in the gel structure [**5**]. Silylation of the gel structure with substances like hexamethyldisiloxane (HMDSO) reduces its reactivity, whereby the gel structure can return to its original shape after shrinkage.

Methodology of LCA

Focus of this study is the reliability of the LCA for products in early research through the example of HOMESKINs insulation material composite with the consideration of further developments. Thereby, possible future production scenarios are calculated and compared with the current ecological performance of the product.

LCA for HOMESKINs insulation material composite is performed by using CML method. It is “from cradle to factory gate” approach, which means that the extraction of raw materials is included as well as the production of the chemicals, their transport to the industrial plant and the insulation material manufacturing. Complete material and energy flows are taken into account, just as auxiliary materials, waste and emissions. The calculation is performed with regard to EN ISO 14040:2006 and EN ISO 14044:2006 standard [**13, 14**]. Environmental impact categories being considered are “Global Warming Potential (GWP)”, “Acidification Potential (AP)”, “Eutrophication Potential (EP)”, “Ozone Depletion Potential (ODP)”, “Photochemical Ozone Creation Potential (POCP)”, “Abiotic Depletion Potential for elements (ADPE)”, and “Abiotic Depletion Potential fossil (ADPF)”. The indicators "Primary Energy Non Renewable Total (PENRT)" and "Primary Energy Renewable Total (PERT)", which describe the energy use, are also taken into account. Allocation is done with economic values. The functional unit is set to 1m² of a two centimetre thick insulation material composite.

Significant parameters

Notable substances for producing HOMESKINs aerogel-based insulation material are initially glass fiber mats. Those are impregnated with the aerogel raw materials that is produced within the panel. Important substances for this are mainly the precursor TEOS, HMDSO for silylation and ethanol as solvent. Besides, energy in the form of electricity is required too. Ethanol is fully recycled through condensation. Additional ethanol is generated with synthesis of TEOS. It is treated as a co-product and assumed to be sold later. Therefore, it is deducted from the calculation through allocation in proportion to the economic value of the products.

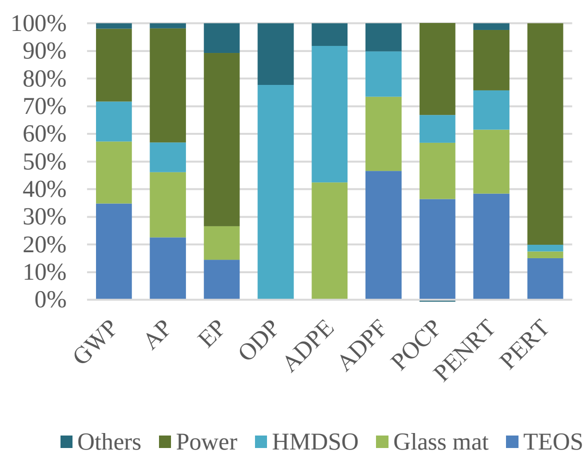

Fig. 1. Percentage share of significant parameters (share in impact > 10 % of total).

Most significant parameters for the considered environmental impacts and energy indicators are power, TEOS, HMDSO, and the glass fibre mat. **Fig.** ***1*** shows that the largest share for almost all impacts is allocated to life cycle stage A1 that implies the raw materials extraction and pre-product manufacturing. For instance, the share of TEOS in the GWP is 34.8%, while the shares of glass mat and HMDSO are 22.5% and 14.4%, respectively. About one quarter of GWP is due to the electricity production which is contributing with its share of 26.4% in the overall GWP.

Raw materials

Concerning data availability, especially TEOS and HMDSO have to be specified. Data bases provide hardly any information for TEOS and HMDSO.

The present inventory analysis of TEOS is based on [**6**], where the life cycle inventory is estimated with the help of stoichiometric equations. This method is based on Hischier *et al.* [**10**], who proposed this procedure for establishing life cycle inventories of chemicals for which no other information are available. Nonetheless, Hischier *et al.* assessed this method as possibly very uncertain because important aspects of life cycle cannot be covered. The calculation implies uncertainties concerning possible emissions, energy demand and waste. TEOS is produced by alcoholysis of silicon tetrachloride with ethanol, whereby hydrochloric acid is generated. Schlanbusch *et al.* considered this by system expanding and crediting TEOS production the avoided hydrochloric acid manufacturing [**6**]. The efficiency is hereby assumed to be 95%. The educt silicon tetrachloride is generated as a co-product within the energy-rich procedure of high-purity silicon. Metallurgical silicon and hydrochloric acid react to silicon tetrachloride. Data availability for silicon tetrachloride is very limited. The life cycle inventory is hence adopted from an earlier study of Schonhardt *et al.* [**15**], which dates back to 2003.

HMDSO is used for avoiding structure changes caused by shrinkages during drying process. Since there's little data evidence, the data from a product group are used. It consists of up to 90% siloxane and up to 10% of a similar substance, however other materials like mineral fillers can also be included. The product group is represented by the one with the highest environmental impacts, which is, except the POCP, mainly caused by the pre-products. Nevertheless, the exact amount of siloxane and its contribution to the environmental impacts is uncertain and implies thus further uncertainties.

TEOS, its educt and HMDSO account for a large share of environmental impacts and additionally, they are based on data that may imply several uncertainties, which are ultimately difficult to predict.

Besides the data availability, uncertainties related to the inputs itself are important. The product is currently in development phase and implies a series of aspects that could change. The future production is hardly foreseeable. Accordingly, in this study, deviations in the treatment of the co-product ethanol and in the energy efficiency are representatively analysed.

Co-product Ethanol

During the insulation material production phase, ethanol is produced, which is then allocated on the basis of the product operating income. Initially, calculation was performed with a 1:4 allocation ratio, where the economic value of ethanol is assumed to be one quarter of the insulation materials.

However, the price development depends on several aspects such as market development of the products, demand and the purity of ethanol.

Consequently, there are three further scenarios performed in order to calculate the influence of possible changes:

- A 1:8 allocation ratio, where the economic value of ethanol is assumed to be one eighth of the insulation materials one.

- A 1:2 allocation ratio, where the economic value of ethanol is assumed to be one half of the insulation materials one.
- Apart from the opportunity of selling the product, ethanol could be internally used. In this case, avoiding ethanol production is credited to manufacturing of the insulation material.

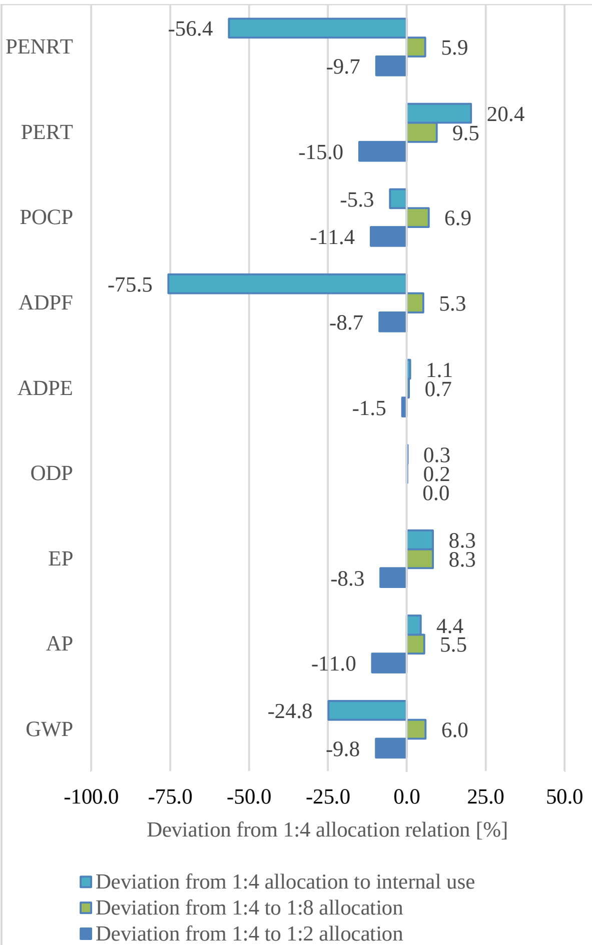

Fig. 2. Deviations in % between different scenarios of ethanol treatment in reference to a 1:4 allocation ratio.

Fig. 2 shows that the impacts of the scenarios partly differ significantly. For instance, the impact of the ADPF varies around 75 % assuming that instead of using the 1:4 allocation ratio, an internal use of ethanol is assumed. Notable differences also exist between varied allocation ratios. The GWP impact deviation amounts between the 1:2 and the 1:8 allocation ratio to 15.8 %. The PERT calculated with the 1:8 allocation ratio deviates by 9.5 % from the 1:4 allocation ratio and the one of the 1:2 allocation ratios is 15 % lower when compared to the reference value.

Increased production efficiency

A further relevant point is the efficiency of a future manufacturing. A larger scale production is expected to be more efficient than the current laboratory-scale production. Exemplarily, this aspect is here represented by a lower energy demand. Hence one scenario was calculated, where the electricity demand is reduced by 17.5 % and by 35 % as well.

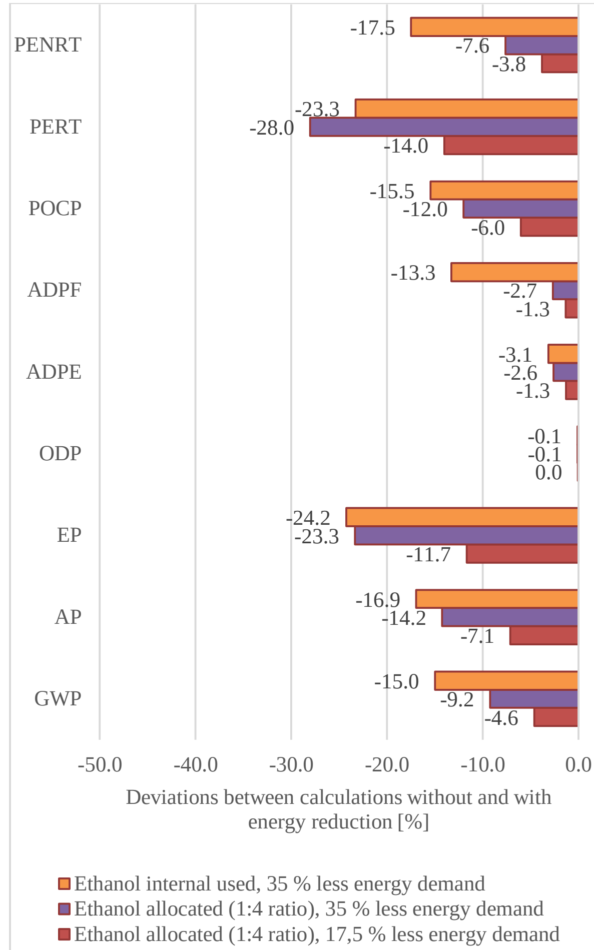

Fig. 3. Deviations in % between different scenarios for energy demand decrease in reference to the related co-product scenarios.

Accordingly, the influence of energy demand seems to be significant for the impacts of GWP, AP, EP, ADPF and POCP as well as the primary energy indicators PERT and PENRT. Only for ODP and ADPE, the discrepancies fell unexceptional below 10%.

For instance, **Fig. 3** shows that an energy demand reduced by 17.5% leads to approximately 11.7% reduced EP in case of a 1:4 allocation ratio of ethanol. A total of 35 % reduction in energy would decrease the EP analogically by 23.3%.

Most deviations exist between the initial LCA calculation with a 1:4 allocation ratio of ethanol with no energy reduction and the LCA calculation with an internal use of ethanol and a simultaneous energy efficiency increase of 35%. In this case, the GWP deviates, for instance, by 36.1% from the initial calculation and the ADPF even by 78.8% (**Fig. 4**). These discrepancies are very significant and demonstrate a wide range of uncertainties and their influence, through which LCA in early development stages has to deal with.

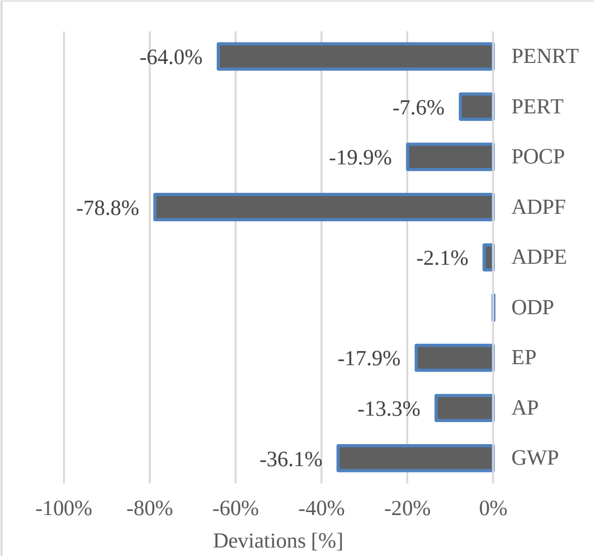

Fig. 4. Deviations in % between initial LCA (1:4 allocation ratio, no energy reduction) and LCA based on the "ethanol internal used"-scenario and a 35 % energy reduction assumption.

Conclusion

The study leads to a conclusion that environmental impacts of innovative products can hardly be assessed and can't be calculated reliably, in principle, as long as the product development is still in its early stage. Nevertheless life cycle assessments may be a valuable tool for steering the development process. For this purpose it is necessary to examine all relevant scenarios that may conclude as a result of different decisions that are still to be made. In the future, enhanced LCA concepts based on interval arithmetic are intended to become an even more appropriate method for assessing innovative materials in development stages.

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Supporting information

Supporting informations are available from VBRI Press.

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