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Integration of life cycle assessment in the design of hollow silica nanospheres for thermal insulation applications

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ABSTRACT

New materials represent an important part of the strategy towards reduced emissions in the building industry. The relative importance of the embodied energy and carbon footprint from the material production in building life cycle assessment is a topic of growing interest. However, there is a recurrent lack of tools to integrate environmental assessment in the early stages of material research and development.

This study summarizes a comprehensive life cycle assessment (LCA) of a new nano insulation material (NIM), based on hollow silica nanospheres (HSNS).

The goal of this analysis is to investigate how the different activities in the production of the material contribute to global warming and demand of energy, in order to find how the environmental impacts may be minimized. The analysis will be used by the scientists to optimize the production process and choice of raw materials with regard to the environment. The main outcome of the LCA is therefore recommendations for a greener production of the HSNS. In addition, this study can serve as a suggestion on how to integrate LCA in the design of other new materials and building components.

1. Introduction

Buildings are responsible for about a quarter of the global energy-related carbon dioxide (CO_2) emissions [1]. In Norway, despite the large availability of hydropower, energy use in the building sector represented 5% of the country's total greenhouse gas (GHG) emissions in 2010 [2].

Material and nanotechnology research devoted to building applications have in the recent years generated new building materials, e.g. self-cleaning coatings applied to clay-bricks [3] and glass [4] and high performance insulation [5]. New materials represent an important part of the strategy towards reduced emissions in the building industry. Especially improvements of the building envelope have the potential to reduce the building energy consumption [6]. It is believed that better insulation is a cost effective way to substantially reduce GHG emissions [7,8].

The relative importance of the embodied energy and carbon footprint from building materials, in building life cycle assessment (LCA) is a topic of growing interest [9]. The reason is that the embodied energy makes up a larger part of the total energy use in low energy and zero emission buildings than in conventional buildings [9,10]. There is a recurrent lack of tools to integrate environmental assessment, e.g. life cycle assessment (LCA), in the early stages of material research and development (R&D) [11,12], i.e. within nanotechnology and other material research fields. New, advanced building components and other new materials are poorly covered by the LCA databases [13].

Nanostructured, high performance insulation materials can reduce energy demands in buildings without altering the wall thickness [5]. The possibility of achieving a satisfactory nano insulation material (NIM) by using hollow silica nanospheres (HSNS) was discussed by Gao et al. [16]. The nano insulation material is currently under development at The Research Centre on Zero Emission Buildings (ZEB) [17] in Norway, and may be viewed as a stepping-stone from vacuum insulation panels (VIP) to high-performance nano insulation materials [14,15,18].

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This study summarizes a life cycle assessment (LCA) of a new nano insulation material (NIM), based on hollow silica nanospheres (HSNS).

In a recent article, Hetherington et al. [19] summarized many of the challenges and issues with LCA when used as a tool within early research. Nanotechnology was one of three sectors that Hetherington et al. [19] treated in the article. The results coincide to a large degree with the issues and challenges identified within the study presented herein. The main challenge is that LCA traditionally has been undertaken retrospectively, using data from existing large scale processes. Attempting to use LCA as a development tool therefore raises problems of comparability, scaling, data and uncertainty [19]. Hetherington et al. [19] strongly encourages publishing of early stage LCA process and results in order to increase understanding.

Hischier and Walser [12] insightfully reviewed the current available life cycle assessment publications on engineered nanomaterials. 17 studies, addressing different kinds of polymer nanocomposites, metal and metal oxide nanoparticles, nanotubes and fibres, were included in the review. Hischier and Walser [12] accentuate the data scarcity. The study problematize the compliance of the publications to the conventional LCA framework and the standard ISO 14044 [20], especially in terms of the life cycle inventories. Most of the available studies on engineered nanomaterials had missing, or very variable, energy input data and emission data. Only two of the studies in the review had inventories based on actual production plant data. In fact, the reported energy consumption was so variable that Hischier and Walser [12] asked if some of the data were calculation mistakes. However, the study does not couple this variability to the lack of industrial energy consumption data due to the early design phase in which much of the engineered nanomaterial products are situated.

Two LCA studies are of special relevance to HSNS. Dowson et al. [13] reported an LCA on silica aerogels made in a laboratory, a material that shares many characteristics with HSNS. The inventory in the methodology by Dowson et al. [13] is limited to a laboratory recipe that produces a small amount of product. Gao et al. [16] reported an LCA on hollow silica nanospheres for thermal insulation applications, following Dowson's methodology. Gao et al. [16] indicated the potential importance of recycling, although this potential was not quantified. Gao et al. [16] also emphasized the importance of environmentally friendly raw materials in order to reduce the embodied energy of HSNS. It was recommended to find a way to remove the template, which is necessary in the production process, without burning it, and alternative raw materials were suggested. Although important as a first step towards a cleaner production of the NIM, the study [16] is carried out by a simplified LCA approach. Direct emissions to air and water, transport and also materials for which LCA data were not found in the literature, were omitted in the study by Gao et al. [16].

In the study presented herein, we aspire to improve the challenging life cycle inventorying for products which are still at the pilot or laboratory stage. The objective of the work is to apply LCA as a sustainability tool in the early design phase of hollow silica nanospheres (HSNS). Compared to the model by Gao et al. [16], the system boundaries are expanded to a complete cradle-to-gate LCA. The new model is constructed in order to calculate the environmental impact of a material for which only a limited dataset is available, by filling data gaps according to a suggested procedure, inspired by, inter alia, literature on LCA for chemicals [11,21]. Data on all raw materials, emissions and infrastructure needed for an industrial HSNS production are included. The method on how to model a system under development and predict its environmental impact, may be of interest for future assessments of new building materials.

With reference to "the summary of main issues in using LCA for early research" in the study by Hetherington et al. [19], it is important to understand that the results from the study presented herein is not directly comparable to published LCA results of conventional insulation materials. To date, the function of the new technology is not yet comprehensively defined and industrial scale data and in-use performance information are unavailable. However, the model presented provides the basis for a comparable LCA when, as the product development proceeds, more information becomes available.

As many of the characteristics of the NIM still are under development, the model is built as flexible as possible. It can therefore be reused and sharpened as the product development of the material proceeds.

2. Materials

The experimental details of the synthesis and characterization of the hollow silica nanospheres are given in the studies by Gao et al. [16,22] and Sandberg et al. [23]. The HSNS was synthesized in three steps. Synthesis of polystyrene templates is the first. The templates were created by employing a simple styrene/polyvinylpyrrolidone/potassium persulfate/H_2O-system. The templates are shown in Fig. 1. In the following coating step, the as-synthesized template solution is mixed with ethanol and ammonium hydroxide. Then, the silica precursor (TEOS) is added to the solution and nanoparticles of silica slowly cover the polystyrene templates. After the coating step is completed, the silica-coated templates may be extracted by centrifugation. Coated templates are depicted in Fig. 2. The third and final step consists of removing the polystyrene templates to obtain hollow silica nanospheres. The polystyrene cores are melted/burnt away at elevated temperatures with hollow silica nanospheres as the result, see Fig. 3.

The new nano insulation material is founded on the known principle of confining air in extremely small pores within the

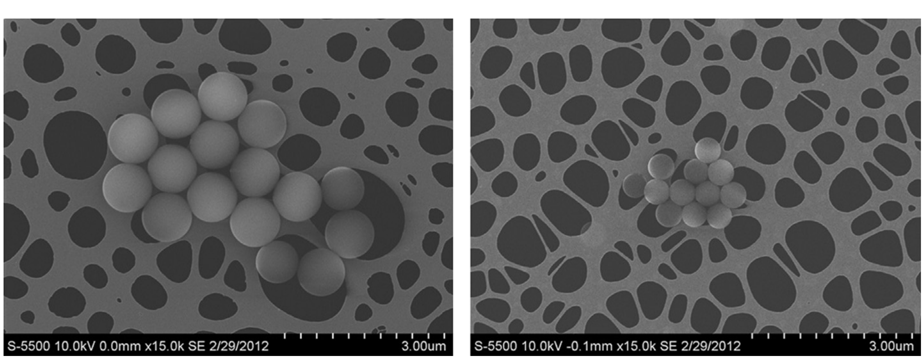

Fig. 1. Uncoated spherical polystyrene templates created with 0.05 g (left) and 0.075 g PVP (right).