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A protocol for lifetime energy and environmental impact assessment of building insulation materials☆

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ABSTRACT

This article describes a proposed protocol that is intended to provide a comprehensive list of factors to be considered in evaluating the direct and indirect environmental impacts of building insulation materials, as well as detailed descriptions of standardized calculation methodologies to determine those impacts. The energy and environmental impacts of insulation materials can generally be divided into two categories: (1) direct impact due to the embodied energy of the insulation materials and other factors and (2) indirect or environmental impacts avoided as a result of reduced building energy use due to addition of insulation. Standards and product category rules exist, which provide guidelines about the life cycle assessment (LCA) of materials, including building insulation products. However, critical reviews have suggested that these standards fail to provide complete guidance to LCA studies and suffer from ambiguities regarding the determination of the environmental impacts of building insulation and other products. The focus of the assessment protocol described here is to identify all factors that contribute to the total energy and environmental impacts of different building insulation products and, more importantly, provide standardized determination methods that will allow comparison of different insulation material types. Further, the intent is not to replace current LCA standards but to provide a well-defined, easy-to-use comparison method for insulation materials using existing LCA guidelines.

1. Introduction

In the United States (US), the adoption of building insulation has been largely driven by building codes and standards, with little attention paid to the energy and environmental benefits of more advanced insulation products. In its latest surveys, the US Energy Information Administration (EIA) reported that 44% and 48% of end use fuel consumption in commercial and residential buildings, respectively, is due to space heating and cooling (EIA, 2003, 2009). Advances in technology have made building insulation materials available that are both energy-efficient and better for the environment, with lower lifetime environmental impacts. The energy and environmental impacts of insulation materials can broadly be divided into two categories: (1) direct impact due to the embodied energy of the insulation materials and (2) indirect or environmental impacts avoided as a result of reduced building energy consumption due to addition of insulation. Hence, it is important to identify insulation materials for buildings that will lead to minimum environmental impacts (direct and indirect) over their lifetime.

A literature review revealed somewhat varying definitions of embodied energy (depending on context), which is associated with the direct environmental impacts in this study. Sartori and Hestnes (2007) defined embodied energy as the sum of all energy needed to manufacture a good, with or without feedstock energy, and generally expressed as primary energy. Jiao et al. (2012) cited the definition of embodied energy of a building as energy used in the component material exploitation, production, transportation and installation, the building construction, and the energy costs of the building maintenance. Dixit et al. (2010, 2012) divided the life cycle energy of building into (i) embodied energy, which is sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal; and (ii) operating energy, which is required for indoor heating and cooling, lighting, and operating appliances. Here, the embodied energy represents the lifetime or cradle-to-grave energy consumption of insulation materials. The lifetime phases include raw material acquisition, manufacturing, installation, disposal, and transportation.

Sartori and Hestnes (2007) reviewed 60 cases of life cycle energy use of buildings and concluded that, while low-energy buildings benefit from reduced overall energy consumption, their energy efficient design results in higher embodied energy. They found that embodied energy varied between 9% and 46% of the overall energy used over the building's lifetime for low energy consumption buildings and between 2% and 38% in conventional buildings. Thormark (2002) evaluated an

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energy efficient building in Sweden and reported that, in a 50-year life span, embodied energy accounted for 40% of the total energy need. Thus, it is important to evaluate the relative environmental impacts resulting from embodied energy of building materials, including insulation materials.

Standards and product category rules exist that provide guidelines for life cycle assessment (LCA) of materials, including building insulation, but details regarding the calculation methods are lacking. Dixit et al. (2012) reviewed the literature related to embodied energy and LCAs of buildings and concluded that the current state of research suffers from lack of consistent data and standard methodology. Ng et al. (2013) found that current building environmental assessment (BEA) tools focused primarily on carbon emissions during the operational phase and not on the emissions throughout the life cycle of buildings. Further, the authors found significant variations in carbon evaluation among the BEA tools. Haapio and Viitaniemi (2008) critically analyzed existing BEA tools and highlighted several shortcomings: (i) several tools did not cover all building life cycle phases and also differed in treatment of the same phase, (ii) there were significant differences in data sources and collection methods utilized, and (iii) users can choose a tool based on the results that best suit their purposes. Clearly, there is a need for standardized assessment methodologies for comparing materials, including insulation materials, based on their total lifetime environmental impacts.

Trusty and Horst (2005) noted that LCAs are complex because they attempt to track a complex world. There can be large discrepancies among reported cradle-to-grave embodied energy values, based on the assessment method employed. For example, the following cradle-to-grave values have been reported for cellulose insulation: 16.64 MJ/kg, and 4.9 MJ/kg (GreenSpec, 2012), 7.6 MJ/kg (Frischknecht et al., 2007) and 0.9 MJ/kg (Harvey, 2007). Several studies have focused on estimating the environmental impacts related to the use of ‘optimum’ insulation thickness in buildings (Dombayci, 2007; Ozel, 2012; Ucar and Balo, 2010); however, the optimum thicknesses were based on life cycle cost analyses rather than environmental impact analysis. Papadopoulos and Giama (2007) performed LCA of two insulation types, stone wool and extruded polystyrene (XPS), but focused on embodied energy during the production phase, with fleeting references to use phase, end-of-life disposal, etc.

Usually, the indirect or avoided environmental impacts of insulation materials due to reduced building energy consumption dominate the total impacts, especially in retrofit of older, poorly designed buildings. Some studies have used correlations and fuel combustion formula for estimating energy saved and emissions avoided (Ardente et al., 2008; Dombayci, 2007; Mazor et al., 2011; Ucar and Balo, 2010). Ozel (2012) used a transient one-dimensional heat conduction equation in a multilayer wall to calculate the thermal transmission loads with different insulation materials. Kosny et al. (1998) modeled a retail mall building with different wall types (masonry and steel-framed) and different insulation materials using whole building modeling tool to estimate the indirect environmental impacts due to the building operational energy use. Different LCAs use customized building models, and there is no standardized set of modeling parameters (Johnas and Terrinoni, 2011; Kosny et al., 1998; SFPA, 2012). Furthermore, the energy saved and environmental impact avoided over the lifetime of the insulation material will depend on the geographical location, climate, building characteristics, and use. Different LCAs also use different building service lifetime periods, for example 50 years (Mazor et al., 2011) or 60 years (SFPA, 2012), another potentially significant source of differences.

The review of current state of assessment methodologies suggests that there are significant uncertainties and variability in estimating both the direct and indirect environmental impacts of insulation materials in buildings. The focus of the current assessment protocol is to identify all factors that contribute to the total energy and environmental impacts of different insulation products and, more importantly, provide standardized determination methods that will allow comparison of different insulation material types. Under the direct impact category, other factors also should be considered that are not necessarily included in the embodied energy but add to the material's environmental impact, for example, emissions of greenhouse gases that may be used as blowing agents in foam insulation materials. In addition, this protocol proposes a standard calculation methodology for estimating the avoided environmental impacts associated with the reduced operational energy of buildings due to the use of insulation materials.

2. Applicability

Fiberglass, foam insulation, cellulose, and mineral wool are the most commonly used insulation materials in US buildings. Table 1 (Buildings Energy Data Book, 2011) shows the latest annual demand data for various insulations and their demand trend from 1992 to 2006. The data show that fiberglass has over 50% of the market share, and foam insulation represents about a fourth of the insulation demand, and this demand is increasing. The market share of different insulation types vary greatly by application. For example, while fiberglass is used extensively as cavity insulation in residential wood-framed walls, foam insulation has the major share of commercial roof insulation.

Fischer et al. (1992) and Kosny et al. (1998) described a procedure for estimating the total environmental warming impact of foam insulation materials based on the direct contribution of greenhouse gas emissions from the insulation used and the indirect contribution of the carbon dioxide emissions resulting from the energy required to operate the building over its expected lifetime. However, the environmental impacts associated with the other life cycle stages of foam insulation (e.g., manufacturing, disposal, and transportation) were not considered. The proposed protocol described here attempts to identify all factors that contribute to the total energy and environmental impacts of different insulation products and quantify those impacts. Such information will likely encourage the use of advanced building insulation materials that provide higher energy savings and have lower lifetime environmental impacts.

This article provides a list of life cycle stages and parameters to be considered for the lifetime energy and environmental impact assessments of insulation materials. Detailed explanations and suggested calculation methods are provided in Sections 3–5. This protocol is intended for performing lifetime impact assessments of insulation materials and can be useful for various ‘green building’ evaluation programs, such as

- The US Green Building Council's LEED (Leadership in Energy and Environmental Design) certification system[1]
- The Commercial Building Energy Asset Score being developed by the US Department of Energy (DOE) Building Technologies Program[2]
- Building for Environmental and Economic Sustainability (BEES) software developed by the National Institute of Standards and Technology (NIST)[3]
- Athena's Impact Estimator[4]

LEED encourages reductions in embodied energy through the use of salvaged, recycled, and local materials, as well as providing points for designing durable buildings. The proposed changes in the latest version of LEED include assigning credit for environmental product declarations (EPD) and LCAs that demonstrate reductions in environmental impacts. It is anticipated that this protocol will be useful for programs like LEED in assigning credits for using insulation materials with lower environmental impacts, and conversely, debit the use of insulation materials with higher impacts.

[1] http://www.usgbc.org/leed.
[2] http://www1.eere.energy.gov/buildings/commercial/assetscore.html.
[3] http://www.nist.gov/el/economics/BEESSoftware.cfm.
[4] http://www.athenasmi.org/our-software-data/impact-estimator/.