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Insulation materials for commercial buildings in North America: An assessment of lifetime energy and environmental impacts☆

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ABSTRACT

In the United States, commercial buildings accounted for about 19% of the total primary energy consumption in 2012. Further, 29% of the 'site' energy in commercial buildings was consumed for space heating and cooling. Applying insulation materials to building envelopes is an effective way of reducing energy consumption for heating and cooling, and limiting the negative environmental impacts from the buildings sector. While insulation materials have a net positive impact on the environment due to reduced energy consumption, they also have some negative impacts associated with their 'embodied energy'. The total lifetime environmental impacts of insulation materials are a summation of: (1) direct impacts due to their embodied energy, and (2) indirect or impacts avoided due to the reduced building energy consumption. Here, assessments of the lifetime environmental impacts of selected insulation materials for commercial buildings in North America are presented. Direct and indirect environmental impact factors were estimated for the cradle-to-grave insulation life cycle stages. Impact factors were calculated for two categories: primary energy consumption and global warming potential. The direct impact factors were calculated using data from existing literature and a life cycle assessment software. The indirect impact factors were calculated through simulations of a set of standard whole-building models.

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1. Introduction

The United States (U.S.) Energy Information Administration (EIA) tracks the energy consumption by the different major U.S. sectors, viz., buildings, industries and transportation [1]. The buildings sector is further divided into residential and commercial buildings. According to EIA, in 2012, U.S. commercial buildings consumed 17.6 quadrillion Btu (quad) of primary energy, which was 19% of the total U.S. primary energy consumption, and is projected to increase by 3.3 quads from 2012 to 2040, the second largest increase after the industrial sector [1]. Reducing energy consumption is key to reducing or limiting the negative environmental impacts from the building sector. Application of insulation materials is an effective method of reducing the heating and cooling-related energy consumption, which accounted for 29% of the delivered (or site) energy consumption in commercial buildings [1]. In the U.S., the adoption of building insulation has been largely driven by building codes and standards, with little attention paid to the environmental benefits of more advanced insulation products. Advances in technology have made building insulation materials available that are both energy-efficient and better for the environment, with lower lifetime environmental impacts; for example, foam insulation materials with blowing agents that have lower global warming potential (GWP) [2].

The lifetime environmental impacts of insulation materials can broadly be divided into two categories: (1) direct impacts due to the embodied energy of the insulation materials and (2) indirect or environmental impacts avoided as a result of reduced operational energy consumption of the buildings due to addition of insulation. It is important to identify insulation materials for buildings that will lead to minimum negative environmental impacts over the insulation lifetime. In a review article, Cabeza et al. [3] noted that embodied energy has been defined somewhat differently by several authors, but there is general agreement that embodied energy in building materials has increased its importance in the life cycle of a building compared to operating energy, due to the better energy performance of buildings.

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Nomenclature

A	area (m^2 or ft^2)
FU	functional unit (kg or lb)
i	number of years
l	fractional material loss rate of an insulation material
N	number of functional units
n	building lifetime in years (60 for new buildings, 30 for existing buildings)
R	thermal resistance (m^2 K/W or h ft^2 F/Btu)
r	Number of replacements of an insulation material
U	Overall heat transfer coefficient (W/m^2 K or Btu/h ft^2 °F)
X	Impact factor (MJ/FU or kg CO_2e/FU)
λ	Thermal conductivity (W/m K or Btu in./h ft^2 °F)
ρ	Density (kg/m^3 or lb/ft^3)

Subscripts

cl	code-level
Cum	cumulative
Dir	direct
Eff	effective
Elec	electricity
Env	envelope
Ind	indirect
Mod	modified
NG	natural gas
pe	pre-existing
SI	Le Système International d'Unités (International System of Units)

Abbreviations

AOE	avoided operational energy
APD	ambient pressure drying
ASHRAE	American Society of Heating, Refrigeration, and Air-conditioning Engineers
DOE	Department of Energy
EI	ecoinvent
EIA	Energy Information Administration
EPD	environmental product declaration
EPS	expanded polystyrene
GHG	Greenhouse gases
GWP	global warming potential
HTSCD	high temperature supercritical drying
HVAC	heating, ventilation, and air-conditioning
IEAD	insulation entirely above deck
IECC	International Energy Conservation Code
LCA	life cycle assessment
LCI	life cycle inventory
LTSCD	low temperature supercritical drying
OE	operational energy
PIMA	polyisocyanurate insulation manufacturers association
PIR	polyisocyanurate
PUR	polyurethane
SHGC	solar heat gain coefficient
SPFA	spray polyurethane foam alliance
U.S.	United States
XPS	extruded polystyrene

Review studies have found that embodied energy can be 9–46% of total lifetime energy consumption of buildings [4,5]. Another important finding was that, if time value of carbon and emission reduction targets is taken into account, the relative impact of embodied energy increases noticeably [4]. Hernandez and Kenny [6] and Cellura et al. [7] took the concept of net-zero or low energy buildings and extended it to 'life cycle zero energy' buildings by including the embodied energy of the building and its components together with the energy use. Life cycle assessment (LCA) studies specific to insulation materials have also been reported [8–11].

Regarding the assessment methods for embodied energy and total life cycle environmental impacts, Cabeza et al. [3] found that there was agreement among researchers that embodied energy is difficult to quantify and there is no generally accepted methodology for its measurement or calculation. There are standards and product category rules that guide the life cycle assessments of materials, including insulation materials, but details related to the calculation methods are not well defined. Haapio and Viitaniemi [12] highlighted the following shortcomings with building environmental assessment tools: (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. Azari et al. [9] noted that there are few studies that have integrated energy and life cycle assessments. For example, Pargana et al. [11] only conducted a cradle-to-gate analysis for comparing different insulation materials and did not consider the use phase; their rationale was that the 'use' phase results were expected to be same for all insulation materials. Hernandez and Kenny [6] calculated the embodied energy for their analysis using a cradle-to-gate approach, but noted that this approach ignores some important aspects such as transport to building site, maintenance and end-of-life disposal, which could have potentially high impacts.

Even in the 'use' phase calculation of environmental impacts, there is opportunity for variability. Different LCAs use customized building models without any standardized set of parameters [13–15]. Different LCAs also use different building service lives, for example 50 years [16] or 60 years [13], another source of significant variability. Further, the energy savings and avoided environmental impacts depend on the building location, climate, building characteristics and operating conditions. Shrestha et al. [17] proposed an assessment protocol for the lifetime environmental impacts of insulation materials in terms of primary energy consumption and global warming potential. The protocol proposed standard calculation methodologies for estimating the avoided environmental impacts associated with the reduced operational energy of buildings during the 'use' phase of the insulation materials. Further, under the direct impact category, factors that are not necessarily included in the embodied energy but add to the environmental impacts were also considered; for example, emissions of high-GWP blowing agents used in foam insulation materials [17].

This manuscript presents complete cradle-to-grave environmental impact assessments of several insulation materials applied to a set of commercial buildings in North America, in two different climate types. The assessment methodology follows the guidelines proposed by Shrestha et al. [17], and encompasses the following life cycle stages: raw material acquisition, manufacturing, installation and use, disposal, and transportation. The direct environmental impact factors were calculated based on data from existing literature and a LCA software. The indirect impact factors were calculated based on standardized simulations of whole-building models. It should be noted that the calculations presented here are not limited by how insulation materials are currently applied and which insulation materials are used in specific applications (wall vs. roof) in commercial buildings. The goal here is to compare the total environmental impacts of insulation materials for identical applications. This is similar to Azari et al. [9], who considered window-to-wall ratios that weren't necessarily compliant with the local building codes but were important to assess the comparative environmental impacts. Tettey et al. [10] varied

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