Title: 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 percent of the total primary energy consumption in 2012. Further, 29 percent 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.

Keywords: insulation materials, commercial buildings, direct environmental impacts, indirect environmental impacts, embodied energy, global warming potential

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 ($\text{m}^2 \cdot \text{K}/\text{W}$ or $\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}/\text{Btu}$)
r	Number of replacements of an insulation material
U	Overall heat transfer coefficient ($\text{W}/\text{m}^2 \cdot \text{K}$ or $\text{Btu}/\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$)
X	Impact factor (MJ/FU or $\text{kg CO}_2\text{e}/\text{FU}$)
λ	Thermal conductivity ($\text{W}/\text{m} \cdot \text{K}$ or $\text{Btu} \cdot \text{in}/\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$)
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

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.

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 the insulation materials in the different parts of their reference buildings and substituted them with alternative materials with appropriate thicknesses to achieve similar envelope thermal characteristics, while assuming that the materials substitutions did not significantly affect other parts of the buildings.

Finally, this manuscript is not intended to be used as a recommendation for using one insulation material over another based purely on the current results. While selecting insulation materials for particular applications, additional considerations of applicability, installation methods, durability, etc., are needed.

2. LIFETIME IMPACT ASSESSMENT METHODOLOGY

In this section, relevant details of the assessment methodology are described.

2.1 Functional Unit

Most environmental product declarations (EPD) and life cycle assessments (LCA) use functional units as the basis for the environmental impact assessment results [13, 18, 19,]. The functional unit for this assessment is defined as **mass (kg) of insulation material needed to cover a 1 m² area at a thickness providing an average thermal resistance (R_{SI}) of 1 m²·K/W for a building service life of 60 years.** The functional unit (FU , kg) can be expressed as,

$$FU = R \cdot \lambda \cdot \rho \cdot A \quad (1)$$

In above equation, R is unit thermal resistance (1 m²·K/W), λ is the thermal conductivity (W/m·K), ρ is the density (kg/m³), and A is a unit area (1 m²).

2.2 Lifetime Impact Categories and Stages

The calculation results of both the direct and indirect environmental impacts of the insulation materials have been presented in terms of two environmental impact categories:

1. Primary or source energy in megajoules (MJ) per functional unit.
2. Global warming potential (GWP₁₀₀) in kilograms carbon dioxide (CO₂) equivalent (kg CO₂e) per functional unit.

The calculated impact factors are negative (−) when these relate to energy consumed and detrimental environmental impacts and positive (+) with respect to energy saved and environmental impacts avoided. Following this sign convention, a higher positive impact factor would indicate a more environmentally friendly product. Figure 1 shows the different life-cycle stages contributing to the life cycle impacts of insulation materials. These life-cycle stages are further described below. Recycling and reuse, represented by the ‘green’ arrows, provide net

reductions or offsets in the environmental impacts; they have not been included in the present calculations, but can be considered if relevant data are available.

Raw material acquisition – The primary energy consumption and emissions associated with obtaining and processing primary or secondary materials (including virgin and recycled materials) that are used to produce an insulation product.

Manufacturing – The primary energy consumption and emissions associated with the production and packaging of an insulation product using raw materials. This life cycle phase also considers the energy and emissions associated with manufacturing waste.

Installation and use – The primary energy consumption and emissions associated with installing the insulation product, accounting for any waste produced during the installation process. This life cycle phase also accounts for any emissions that occur during the product's lifetime and during maintenance under normal conditions (e.g., the release of fugitive gases). The primary energy and emissions avoided during the use phase (indirect environmental impacts) were calculated based on EnergyPlus¹ simulations of standard prototype building models, as discussed later. This is distinctive from previous building and insulation-related LCAs. Some LCAs did not consider the use phase [6, 11]. Some other assessments used highly customized building models or different service lives [13-16] that make it difficult to appropriately compare the lifetime impacts of different insulation materials.

Disposal – The primary energy consumption and emissions associated with dismantling and demolition of an insulation product at the end of the product's life.

Transportation – The primary energy consumption and emissions associated with the transport of the raw materials to the manufacturing site, transport of the finished product from the manufacturer to the construction site, and transport of construction wastes and deconstructed product to end-of-life disposal facilities or landfill. When reuse occurs, this life cycle phase also accounts for the energy and emissions associated with the transport of the dismantled product to the second construction site.

Fugitive emissions – Hydrofluorocarbons and other blowing agents with GWP are used in foam insulations, such as extruded polystyrene, polyisocyanurate, and polyurethane foams to boost their thermal properties. The emission of these blowing agents can occur during the manufacturing process, installation and use phase, and end-of-life disposal, with associated

¹ <http://apps1.eere.energy.gov/buildings/energyplus/>

global warming impact. 100-year GWP (GWP_{100}) was used to calculate impacts associated with fugitive emissions of foam blowing agents.

GWP_{100} is the ratio of the amount of heat trapped by a certain mass of the blowing agent in the 100 years after it has been released to atmosphere, to the amount of heat trapped by the same mass of CO_2 in 100 years, and can be used to convert the mass of blowing agents into equivalent mass of CO_2 (kg CO_2e). CO_2 has a GWP_{100} of 1 and the other blowing agents considered have the following values: HFC-134a – 1370, HFC-152a – 124 and pentane – 7 [2, 20, 21]. Therefore, 1 kg of HFC-134a has the same GWP_{100} as 1370 kg of CO_2 . The impacts associated with emissions of the blowing agent (fugitive emissions) were based on the Intergovernmental Panel on Climate Change (IPCC, 2006) [22] and Technology and Economic Assessment Panel (TEAP) [23] reports. It was assumed that 100% of the blowing agent used in foam insulation material was eventually emitted to the atmosphere, with no end-of-life recovery.

To assess direct environmental impacts, life cycle data were collected from publicly available resources, including published literature and industry sources. To supplement this information, data for selected insulation materials were also generated from the SimaPro LCA software.² SimaPro is a LCA tool that allows comprehensive modeling of the life cycle implications of products and materials. SimaPro includes a number of life cycle inventory (LCI) databases — including Ecoinvent (EI) [24], the U.S. LCI Database [25], and the U.S.-EI Database [26] - covering hundreds of common materials and processes. For this study, the LCI databases and impact assessment methods in SimaPro were used to evaluate the source energy consumption and greenhouse gas (GHG) emissions during the five key phases in the life cycle of insulation products.

Here, the direct environmental impact factors are presented on a per functional unit basis. The impact factors have been modified (Mod) for any insulation replacement during the 60 year building service life as well as for material losses during installation as follows. For new commercial buildings, it is common to replace the roof insulation whenever any repairs to the roof are performed, usually after 20-30 years. Wall insulation, however, is rarely replaced. This is again an important distinction from previous LCAs, many of which do not consider replacement of building components.

² <http://www.pre-sustainability.com/simapro>

$$X_{Mod} = X \cdot (1 + r) \cdot (1 + l) \quad (2)$$

In the above equation, ‘X’ is the nominal impact factor, either primary energy consumption (MJ/FU) or GWP₁₀₀ (kg CO₂e/FU), ‘r’ is the number of replacements of a given insulation material and ‘l’ is the fractional loss rate of the insulation material during the different life cycle stages. In this study, a 5% material loss rate was assumed. The impact factors should be modified appropriately if accurate material loss rate data are available. No recycling or reuse of insulation materials or their components was assumed, but can be accommodated if reliable data are available. Also, no credit was assigned (i.e., the direct impact factors are not reduced) if the insulation application is for less than 60 years, for example in insulation upgrades of existing buildings that may not last a further 60 years.

Table 1 lists all the life cycle stages and subcategories that were considered in this assessment.

Table 1. Life cycle stages and subcategories

Life-Cycle Stage	Subcategory
Raw material acquisition	Extraction and processing
	Material losses
	Fugitive emissions
Manufacturing	Manufacturing process
	Material losses
	Fugitive emissions
Installation and use	Installation processes
	Material losses
	Fugitive emissions
	Avoided impacts during use phase
Disposal	Disposal processes
	Fugitive emissions
Transportation	Raw material to manufacturing
	Manufacturing to installation and use
	Use to disposal

2.3 Indirect Environmental Impact Calculations

Insulation materials increase the resistance (R-value) to heat flow through the building envelope (walls, roof, foundation, etc.) and help reduce the energy required by the heating, ventilation, and air-conditioning (HVAC) systems to maintain thermal comfort within the building. The primary energy saved, and hence CO₂ emissions avoided, over the building service life are the indirect environmental impacts of the insulation materials, which usually dominate

the total lifetime environmental impacts, often exceeding the direct impacts by orders of magnitude [5, 13, 14]. As discussed earlier, there is a lack of standardization in how the indirect impacts are calculated by different LCAs.

To reduce variability in energy savings calculations due to subjective selection of input parameters, standardized and appropriate sets of building models are required. For commercial buildings, Shrestha et al. [17] recommended the use of a standardized set of building models derived from DOE's commercial reference and prototype building models [27, 28], and typical meteorological year (TMY)³ weather files for the locations of interest.

The energy consumption of selected standard commercial buildings were calculated using EnergyPlus. The energy savings due to addition of or upgraded insulation materials, referred to as avoided operational energy (AOE), were calculated as

$$AOE = OE_{pe} - OE_{cl} \quad (3)$$

Where

OE_{pe} = operational energy with pre-existing insulation

OE_{cl} = operational energy with current code-level insulation

Operational energy with pre-existing insulation is the energy that would be consumed over the service life of a building in its pre-existing state, under specific climate conditions. Since this protocol applies to both new and existing buildings, OE_{pe} is defined for the two scenarios as:

1. New buildings: OE_{pe} is the energy consumed with an uninsulated building envelope.
2. Existing buildings: OE_{pe} is the energy consumed with the building envelope insulated to a baseline R-value. To use a common baseline, the R-value was chosen to be according to requirements of the 1989 version of ASHRAE 90.1 [29].

Operational energy with current code-level insulation is the energy required over the service life of the same building, under the same climate conditions, and with identical operating and occupancy conditions, but with code-level insulation required by the current version of ASHRAE Standard 90.1 (latest version is 2013) [30].

The same amount of OE using electricity or natural gas requires a different amount of source or primary energy and has different environmental impacts. Therefore, AOE using electricity (AOE_{Elec}) and natural gas (AOE_{NG}) were calculated separately as:

³ http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm

$$AOE_{Elec} = OE_{pe,Elec} - OE_{cl,Elec} \quad (4)$$

$$AOE_{NG} = OE_{pe,NG} - OE_{cl,NG} \quad (5)$$

OE_{pe} and OE_{cl} using electricity and natural gas were output results of the EnergyPlus models, and were used to calculate the corresponding AOE . The AOE calculated in equations (4) and (5) represent ‘site’ energy savings, i.e. the reduction in energy consumed by the buildings on site. Appropriate conversion factors are needed to estimate the primary or source energy as well as CO₂ emissions corresponding to the calculated ‘site’ operational energy. Such conversion factors are available from various DOE sources and were used in the current analyses.

The choice of baseline (pre-existing) and upgraded code-level insulation cases were guided by the need for well-defined and standard insulation levels. For new buildings, the upgraded case was selected as 2013 code-level insulation, which is a well-defined target. The most appropriate baseline case for new buildings then became the uninsulated building. In contrast, for existing buildings, there were two well-defined target R-values (1989 and 2013 versions of ASHRAE 90.1), one of which served as the baseline (1989 version). The present calculations are based on ASHRAE 90.1-recommended levels of exterior envelope (wall and roof) R-values for different building types and climate zones. The respective insulation thicknesses were estimated to match the desired R-values and may not be same as the standard commercially available thicknesses of the selected insulation materials.

2.4 Commercial Building Cases

The indirect environmental impact factors were calculated using the prototype building models of three building types in two climate zones, listed in Table 2. Also provided are the respective exterior envelope (wall and roof) construction type, area and the ASHRAE 90.1-recommended insulation R-values. 1989 and 2013 versions of ASHRAE 90.1 [29, 30] were followed for existing and new buildings, respectively. While the 2013 version of ASHRAE 90.1 provides the minimum wall and roof R-values based on construction, the 1989 version doesn’t explicitly specify R-values. Rather, the 1989 version prescribes maximum overall heat transfer coefficients (U , W/m²·K) for the envelope assemblies. Therefore, the insulation R-values for existing buildings were calculated by subtracting the R-value of other layers of the envelope assembly from the inverse of the overall heat transfer coefficient (U).

Table 2. Building model construction and insulation-related details

Building type	Construction		Exterior envelope area (m ²)		Climate zone (City)	Insulation R-value (m ² -K/W)			
						New building		Existing building	
	Wall	Roof	Wall	Roof		Wall	Roof	Wall	Roof
Highrise apartment	Steel framed	Insulation entirely above deck (IEAD)	3,855	784	2A (Houston)	1.71	4.31	NA	NA
					5A (Chicago)	2.82	5.30	NA	NA
Medium office	Steel framed	IEAD	1,978	1,661	2A (Houston)	1.71	4.31	0.74	2.40
					5A (Chicago)	2.82	5.30	1.73	3.11
Standalone retail	Mass	IEAD	1,177	2,294	2A (Houston)	0.85	4.31	0.09	2.40
					5A (Chicago)	1.64	5.30	1.34	3.11

The standard EnergyPlus models can be downloaded from DOE's websites for existing and new buildings.^{4,5} The building models listed on the DOE websites match the specifications of Deru et al. [27] and the enhancements and changes described by Goel et al. [28]. Reference (existing) and prototype (new) building models are available for seventeen (17) different types of commercial buildings in fifteen (15) climate zones [27, 28]. The purpose of these building models is to allow consistency in modeling approaches. Deru et al. [27] divided the model inputs into four categories:

1. Program: Location, floor area, occupancy, operating schedule, etc.
2. Form: Number and height of floors, window locations and fraction, orientation, etc.
3. Fabric: Exterior walls, roof, floors, windows, partitions, etc.
4. Equipment: Lighting, water heating and HVAC equipment, control settings, etc.

Chapter 5 of Deru et al. [27] and chapter 2 of Goel et al. [28] provide complete details of the inputs to the reference building models. For this study, the models were modified to match the roof and wall insulation R-values listed in Table 2. HVAC efficiencies were based on 1989 and 2013 versions of ASHRAE 90.1 for existing and new buildings, respectively; however, HVAC equipment sizes were automatically calculated by EnergyPlus to meet the building loads. For windows, the minimum conductance (U-factor) and, where applicable, maximum solar heat gain coefficient (SHGC) required by ASHRAE 90.1 were assumed. An added assumption in the building models was that addition of insulation did not change the air infiltration through the building envelope between the baseline and upgraded cases.

⁴ <http://energy.gov/eere/buildings/existing-commercial-reference-buildings-constructed-or-after-1980>

⁵ <https://www.energycodes.gov/commercial-prototype-building-models>

The building types and climate zones were chosen based on their relative fractions of the total volume of commercial buildings in the U.S. and representing different types of occupancy and cooling/heating dominated climates. Highrise apartments, medium offices and standalone retails buildings represent about 9.0, 6.1 and 15.3%, respectively, of the total new commercial buildings from 2003 to 2007 [31]. Further, the three building types chosen represent different occupancy and usage profiles; for example, the medium office is expected to have higher occupancy and energy usage during the daytime and the opposite is expected for highrise apartments. Climate zone 2A, defined by ASHRAE 90.1, is cooling dominated (hot or warm weather) and contains 15.2% of new buildings; climate zone 5A is heating dominated (cold weather) with 19.4% of new buildings [30, 31].

2.5 Insulation Materials

Four insulation materials were evaluated in this study: polyisocyanurate (PIR) foam insulation, expanded (EPS) and extruded (XPS) polystyrene foam insulation, and aerogel. PIR, XPS and EPS are closed-cell, rigid foam boards and were chosen based on their predominant market share of commercial building insulation [17]. PIR is a commonly used roof insulation material and has a 60-65% market share in low-slope commercial roofs in the U.S. [18]. PIR board insulation consists of a foam core sandwiched between two facers. XPS is manufactured through an extrusion process where polystyrene is melted and combined with a blowing agent (HFC-134a, HFC-152a or CO₂). EPS is manufactured by "expanding" the polystyrene polymer through the combination of a blowing agent (pentane) and heat.

Aerogel is not commonly used as a building insulation material at present, but has superior thermal properties (low conductivity) compared to current commercial insulation materials. Aerogel insulation preparation involves three main steps: gel preparation, ageing and drying [32]. Drying takes place through either high temperature supercritical drying (HTSCD), low temperature supercritical drying (LTSCD) or ambient pressure drying (APD). The thermal conductivity of aerogel is about 0.013 W/m·K [32], compared to 0.024-0.036 W/m·K for foam insulation materials [33]. One of the study goals was to evaluate newer insulation materials, hence the choice of aerogel. Vacuum insulation panels were considered for this study, but were not included due lack of sufficient data. Current research is ongoing to reduce the material and processing costs of vacuum insulation, which are correlated to the direct environmental impacts of raw material acquisition and manufacturing. This is an area that needs further investigation

for quantifying the environmental impacts of the newer, next-generation insulation materials, but was outside the current scope.

Table 3**Error! Reference source not found.** lists the thermal conductivity, density, and functional unit of the selected insulation materials following eq. (1), using data from literature [32, 33].

Table 3. Functional units of the selected insulation materials

Insulation	Thermal conductivity (W/m·K)	Density (kg/m ³)	Functional Unit (kg)
PIR	0.0236	29	0.68
XPS	0.0320	30	0.96
EPS	0.0360	25	0.90
Aerogel	0.0130	144	1.87

In this study, the insulation materials are assumed to have been applied as ‘continuous insulation’, which refers to a continuous layer of insulation on the exterior of the building envelope. This is in contrast to ‘discontinuous’ or ‘cavity’ insulation applied between framing (wood or metal studs). Comparing discontinuous and continuous insulation cases is not appropriate as their impacts in terms of insulating the building are different. Therefore, only the continuous insulation cases were chosen. It was also assumed that all selected insulation materials are applicable to both walls and roofs. As discussed earlier, the goal is to compare the environmental impacts of insulation materials for identical applications.

3. RESULTS AND DISCUSSION

Calculation results are categorized as direct, indirect and net environmental impacts and have been presented as such in this section.

3.1 Direct Environmental Impacts

Table 4 and Table 5 list the direct environmental impact factors of the selected insulation materials in terms of primary energy consumption and GWP₁₀₀ for the different life cycle stages. Following the sign convention stated in section 2.2, all direct environmental impacts are negative. In Table 4, the impact factors have been modified to account for an assumed 5% material loss rate, according to eq. (2). The direct impact factors listed in Table 4 are applicable to wall insulation in new buildings and both wall and roof insulation in existing buildings. In

Table 5, the impact factors have been modified to include a 5% material loss rate and a single replacement during the building lifetime. The values in Table 5 were applied to roof insulation in new buildings, since, in new commercial buildings, it is common to replace the roof insulation after 20-30 years. The direct impact factors are independent of the lifetime of the insulation, since they're assumed to be incurred regardless of the application time period. As illustrative examples, the impact factors from Table 4 are presented graphically in Figure 2 and Figure 3.

Table 4. Direct environmental impact factors of selected insulation materials with assumed 5% material loss rate

	PIR (with pentane)	XPS (with HFC-152a)	EPS (with pentane)	Aerogel
Primary energy (MJ per Functional Unit)				
Raw material acquisition	-63.29	-88.55	-88.06	--
Manufacturing	-0.32	-12.42	-12.81	-105.95
Installation and use	Neg.	Neg.	Neg.	Neg.
Disposal	-0.05	-0.07	-0.07	-0.14
Transportation	-1.42	-1.99	-1.87	-3.88
Total	-65.08	-103.03	-102.80	-109.97
GWP₁₀₀ (kg CO₂e per Functional Unit)				
Raw material acquisition	-2.59	-3.59	-3.32	--
Manufacturing	-0.04	-2.52	-0.86	-8.43
Installation and use	-0.21	-3.94	-0.04	0.00
Disposal	-0.12	-2.95	-0.03	-0.01
Transportation	-0.04	-0.14	-0.13	-0.26
Total	-3.00	-13.13	-4.38	-8.71

Table 5. Direct environmental impact factors of selected insulation materials with assumed 5% material loss rate and single replacement during building lifetime

	PIR (with pentane)	XPS (with HFC-152a)	EPS (with pentane)	Aerogel
Primary energy (MJ per Functional Unit)				
Raw material acquisition	-126.58	-177.10	-176.13	--
Manufacturing	-0.63	-24.84	-25.61	-211.89
Installation and use	Neg.	Neg.	Neg.	Neg.
Disposal	-0.10	-0.14	-0.13	-0.28
Transportation	-2.85	-3.98	-3.73	-7.76
Total	-130.16	-206.06	-205.61	-219.93
GWP₁₀₀ (kg CO₂e per Functional Unit)				
Raw material acquisition	-5.17	-7.17	-6.64	--
Manufacturing	-0.08	-5.04	-1.71	-16.86
Installation and use	-0.42	-7.87	-0.09	0.00
Disposal	-0.25	-5.90	-0.07	-0.02
Transportation	-0.07	-0.27	-0.25	-0.53
Total	-6.00	-26.26	-8.76	-17.41

The SimaPro LCA software was primarily used to generate data for the direct impact factors for raw material acquisition and manufacturing of XPS, EPS and PIR insulation. For EPS and XPS, fugitive emissions of blowing agents were assumed to be distributed as 25% during manufacturing, 0.75% of the original quantity annually during the 60-year use phase and the remainder during disposal (30%) [23]. Emission rates for PIR were: 6% during manufacturing, 1% annually during use phase and remainder during disposal (34%). PIR emission rates were based on data for polyurethane (PUR) foam board [22], since PUR and PIR are manufactured using a similar process and have a similar structure.

Data for aerogel were obtained from Dowson [32] and were based on the following industrial processing steps: (i) raw materials mixed into a sol, (ii) fiber reinforcement, (iii) low temperature supercritical drying (LTSCD), (iv) CO₂ recovery, and (v) pollution control. Dowson [32] found that high-temperature supercritical drying (HTSCD) had lower production energy and CO₂ burden than LTSCD in laboratory-scale testing, but noted that the findings did not accurately represent the impacts for industry-scale volume production.

Due to lack of availability of disposal-related primary energy data for the insulation materials, proxy data from the disposal of mineral wool in a non-hazardous waste landfill were used. Transportation related data were obtained from a report by Polyisocyanurate Insulation Manufacturers Association (PIMA) [18] and were applied to all insulation materials. Transportation data included transportation of (i) raw materials to the plant, (ii) manufactured PIR to building site, and (iii) used PIR to disposal site. The transportation calculations were based on weight (tonne-km per kg). XPS and EPS have similar densities to PIR (see Table 3), hence the weight-based PIR transportation data were deemed applicable. Aerogel, however, has much higher density than PIR, but the lack of relevant data for aerogel necessitated this approximation. The direct impact factors due to primary energy consumption during installation and use was deemed to be negligible (Neg.) compared to the other life cycle stages for all insulation materials. The direct GWP₁₀₀ of foam insulation materials during installation and use is due to fugitive emissions and was assumed to be zero for aerogel.

Table 4 and Table 5 indicate that PIR has the lowest primary energy consumption on a per functional unit basis, followed by EPS and XPS, with aerogel having the highest primary energy consumption. However, XPS has the highest GWP of the selected insulation materials due to

emissions of the higher GWP blowing agents HFC-152a (listed in Table 4 and Table 5) and HFC-134a.

Table 6 lists the relative contributions of the fugitive emissions of the different blowing agents used in different insulation materials (assuming no loss of insulation or replacement); GWP of XPS with CO₂ as the blowing agent is also shown. It is evident that the higher GWP blowing agents significantly increase the total GWP₁₀₀ of the insulation materials. For further discussions related to XPS, results based on HFC-152a (intermediate GWP) only are presented.

Table 6. Effect of blowing agents and fugitive emissions on total GWP of foam insulation materials

	PIR (Pentane)	XPS (HFC-134a)	XPS (HFC-152a)	XPS (CO ₂)	EPS (Pentane)
Fugitive emissions (kg CO ₂ e/FU)	-0.34	-92.06	-8.33	-0.03	-0.09
Total GWP ₁₀₀ (kg CO ₂ e/FU)	-2.85	-101.11	-12.50	-4.21	-4.17
% GWP ₁₀₀ due to fugitive emissions	11.79	91.06	66.64	0.81	2.26

Since the direct impact factors are dependent on material loss rates and replacement, for a building with both wall and roof insulation, the effective impact factors needed to be calculated as a weighted average of the respective impact factors of the wall and roof insulation. First, the number of functional units (N) for the each insulation application was calculated as,

$$N = (R_{Env} \cdot \lambda \cdot \rho \cdot A_{Env}) / FU \quad (6)$$

R_{Env} and A_{Env} are the prescribed thermal resistance (m²·K/W) and area (m²) of the different envelope (Env) components.

Table 7 lists the number of functional units (N) for the different building types in the two climate zones, calculated according to eq. (6). Since the functional unit is a normalized unit representing the amount of insulation providing 1 m²·K/W over a unit area, ' N ' is independent of the insulation material type.

Table 7. Number of functional units (N) for the different building types and climate zones

Location	New buildings		Existing buildings	
	Wall	Roof	Wall	Roof
Highrise apartment				
2A (Houston)	6585	3381	--	--
5A (Chicago)	10862	4154	--	--
Medium office				

2A (Houston)	3378	7166	1916	3182
5A (Chicago)	5573	8803	2159	3641
Standalone retail				
2A (Houston)	995	9898	891	4395
5A (Chicago)	1928	12160	352	5030

Once the number of functional units for wall and roof are determined, the effective impact factors can be calculated as,

$$X_{Eff} = (X_{Wall} \cdot N_{Wall} + X_{Roof} \cdot N_{Roof}) / (N_{Wall} + N_{Roof}) \quad (7)$$

‘ X_{Eff} ’ is either the primary energy consumption (MJ/FU) or GWP₁₀₀ (kg CO₂e/FU).

Table 8 and Table 9 show the weighted-average direct environmental impact factors for the selected insulation materials for different building types and climate zones. The results are for the cases with both wall and roof insulation upgraded to 2013 ASHRAE 90.1 requirements (upgraded from 1989 code requirements for existing buildings and no insulation for new buildings). There is no ‘highrise apartment’ case for existing buildings as this building model was only added in the recent version of standard commercial building models, applicable to new buildings only.

Table 8. Direct environmental impact factors on a per functional unit basis for existing buildings

Location	Building Type	Product	Direct Lifetime Impact Factors	
			Primary energy (MJ/FU)	GWP ₁₀₀ [kg CO ₂ e/FU]
Houston	Medium Office	PIR	-65.1	-3.0
		XPS	-103.0	-13.1
		EPS	-102.8	-4.4
		Aerogel	-110.0	-8.7
	Standalone Retail	PIR	-65.1	-3.0
		XPS	-103.0	-13.1
		EPS	-102.8	-4.4
		Aerogel	-110.0	-8.7
Chicago	Medium Office	PIR	-65.1	-3.0
		XPS	-103.0	-13.1
		EPS	-102.8	-4.4
		Aerogel	-110.0	-8.7
	Standalone Retail	PIR	-65.1	-3.0
		XPS	-103.0	-13.1
		EPS	-102.8	-4.4
		Aerogel	-110.0	-8.7

Table 9. Direct environmental impact factors on a per functional unit basis for new buildings

Location	Building Type	Product	Direct Lifetime Impact Factors	
			Primary energy (MJ/FU)	GWP ₁₀₀ [kg CO ₂ e/FU]
Houston	Highrise Apartment	PIR	-87.2	-4.0
		XPS	-138.0	-17.6
		EPS	-137.7	-5.9
		Aerogel	-147.3	-11.7
	Medium Office	PIR	-109.3	-5.0
		XPS	-173.0	-22.1
		EPS	-172.7	-7.4
		Aerogel	-184.7	-14.6
	Standalone Retail	PIR	-124.2	-5.7
		XPS	-196.6	-25.1
		EPS	-196.2	-8.4
		Aerogel	-209.9	-16.6
Chicago	Highrise Apartment	PIR	-83.1	-3.8
		XPS	-131.5	-16.8
		EPS	-131.2	-5.6
		Aerogel	-140.4	-11.1
	Medium Office	PIR	-104.9	-4.8
		XPS	-166.1	-21.2
		EPS	-165.8	-7.1
		Aerogel	-177.3	-14.0
	Standalone Retail	PIR	-121.3	-5.6
		XPS	-192.0	-24.5
		EPS	-191.5	-8.2
		Aerogel	-204.9	-16.2

3.2 Indirect Environmental Impacts

Existing Buildings

Table 10 lists the modeled site-energy consumption results for the existing buildings. The baseline case had walls and roof insulated according to the 1989 version of ASHRAE 90.1 ('1989 Baseline') and the other cases represent the building models with upgraded wall, roof and 'wall & roof' insulation according to 2013 version of ASHRAE 90.1; the upgraded cases are represented by 'Wall - 2013', 'Roof - 2013' and 'Wall & Roof - 2013' in Table 10. The energy consumption was calculated separately based on fuel type – natural gas and electricity. The energy savings due to upgraded envelope insulation is the difference in energy consumption between the baseline and upgraded cases. While modeling the existing buildings, it was assumed that the building received only an envelope insulation upgrade and all other buildings characteristics (occupancy, equipment, lighting, HVAC efficiencies, etc.) remained the same.

Table 10. Calculated annual site-energy consumption for the existing buildings

Location	Natural gas (MJ)				Electricity (MJ)			
	1989 Baseline	Wall - 2013	Roof - 2013	Wall & Roof - 2013	1989 Baseline	Wall - 2013	Roof - 2013	Wall & Roof - 2013
<i>Medium office</i>								
2A (Houston)	9,040	8,830	8,960	8,700	1,203,150	1,191,810	1,162,309	1,151,669
5A (Chicago)	234,561	228,691	230,371	224,221	1,218,400	1,198,950	1,192,260	1,173,319
<i>Standalone retail</i>								
2A (Houston)	244,301	233,111	232,611	218,211	815,807	786,196	746,826	742,596
5A (Chicago)	1,545,655	1,492,405	1,532,875	1,479,665	528,924	515,674	524,744	511,534

New Buildings

Table 11 lists the site-energy consumption results from the simulations of the new buildings. The baseline case is the one without any wall or roof insulation ('No Insulation') and the other cases represent the building models with wall, roof and 'wall & roof' insulation added according to the requirements of 2013 version of ASHRAE 90.1.

Table 11. Calculated annual site-energy consumption for new buildings

Location	Natural gas (MJ)				Electricity (MJ)			
	No Insulation	Wall Insulation	Roof Insulation	Wall & Roof Insulation	No Insulation	Wall Insulation	Roof Insulation	Wall & Roof Insulation
<i>Highrise apartment</i>								
2A (Houston)	360,981	201,191	245,741	90,550	2,099,507	1,632,003	1,791,124	1,305,930
5A (Chicago)	2,437,908	1,417,695	1,885,436	852,563	2,219,288	1,636,173	1,796,734	1,198,780
<i>Medium office</i>								
2A (Houston)	26,630	22,350	8,700	5,020	1,145,659	977,818	839,317	664,385
5A (Chicago)	567,272	465,651	409,591	278,761	1,503,222	1,117,059	937,077	537,714
<i>Standalone retail</i>								
2A (Houston)	302,651	279,341	64,890	28,370	1,110,899	1,065,479	494,674	432,783
5A (Chicago)	1,739,296	1,403,384	530,162	182,601	1,049,338	1,033,948	326,343	279,532

Once the site-energy savings were calculated, they were converted to primary or source energy savings using the following site-to-source conversion factors [34, 35]:

- Natural gas: 1.05
- Electricity: 3.545 (Houston); 3.272 (Chicago)

As an example, a conversion factor of 3.545 for electricity implies that 3.545 units of primary energy generation are required to provide 1 unit of site energy.

The CO₂ emissions were estimated based on the following primary energy-to-emission conversion factors [36]:

- Natural gas: 53.06 kg CO₂ per MMBtu (0.0503 kg CO₂/MJ)
- Electricity: 1,218.17 lb CO₂ per MWh (0.1535 kg CO₂/MJ) (Houston); 1,503.47 lb CO₂ per MWh (0.1894 kg CO₂/MJ) (Chicago)

Using these conversion factors, the resulting total primary energy savings and avoided CO₂ emissions for the different existing building cases (building type and climate zone) are shown in Figure 4 and Figure 5. For the existing buildings, the additional building service life after upgrading the envelope insulation was assumed to be 30 years (assuming the insulation upgrade is done midway through the 60 year building life). Therefore, the calculated primary energy savings and avoided CO₂ emissions for the existing buildings are over 30 years.

The resulting total primary energy savings and avoided CO₂ emissions for the different new building cases (building type and climate zone) are shown in Figure 6 and Figure 7. The energy savings and avoided emissions were calculated over 60 years, which is assumed to be the service life of the buildings and the insulation materials. Based on the sign convention being followed, the energy savings and avoided emissions are positive.

In order to calculate the net lifetime environmental impacts of the insulation materials, the indirect impact factors also need to be converted to a per functional unit basis so that they can be combined with the direct environmental impacts. Table 12 lists the indirect impact factors for the different building types in the two climate zones. The results provided are for cases where both wall and roof insulation were added/upgraded to meet 2013 version of ASHRAE 90.1. Since the amount of insulation materials are chosen to provide prescribed R-values, regardless of type, the indirect impact factors do not vary based on the insulation materials.

Table 12. Indirect environmental impact factors on a per functional unit basis

Building type	Climate zone (City)	New buildings		Existing buildings	
		Primary energy (MJ/FU)	GWP ₁₀₀ (kg CO _{2e} /FU)	Primary energy (MJ/FU)	GWP ₁₀₀ (kg CO _{2e} /FU)
Highrise apartment	2A (Houston)	18645	2685	--	--
	5A (Chicago)	19993	2862	--	--
Medium office	2A (Houston)	9838	1497	317	48
	5A (Chicago)	14449	2561	280	45
Standalone retail	2A (Houston)	14828	2112	587	74
	5A (Chicago)	17689	2382	479	37

3.3 Net Lifetime Environmental Impacts

Table 13 and Table 14 present the summaries of the two impact categories (primary energy and GWP) at the different life cycle stages of PIR insulation in existing and new medium office buildings in a single climate zone. The data presented are for cases where both the roof and wall insulation were added/upgraded. For the new building, a material loss rate of 5% and a single roof insulation replacement were included. The indirect impact factors were much higher than the direct impacts factors in both new and existing building cases.

Table 13. Lifetime impacts of polyisocyanurate foam insulation in an existing medium office building in climate zones 2A (Houston) and 5A (Chicago)

Product: Polyisocyanurate foam (with pentane)		Life cycle impact category			
Functional unit (F.U.) (kg): 0.68		Houston		Chicago	
Life cycle stage	Subcategory	Primary energy (MJ/FU)	GWP [kg CO ₂ e/FU]	Primary energy (MJ/FU)	GWP [kg CO ₂ e/FU]
Raw Material Acq.		-63.29	-2.59	-63.29	-2.59
Manufacturing		-0.32	-0.04	-0.32	-0.04
Installation and use	Installation	--	-0.21	--	-0.21
	Impacts avoided during use	317	48	280	45
Disposal		-0.05	-0.12	-0.05	-0.12
Transportation		-1.42	-0.04	-1.42	-0.04
Net Lifetime Impact		252	45	215	42

Table 14. Lifetime impacts of polyisocyanurate foam insulation in a new medium office building in climate zones 2A (Houston) and 5A (Chicago)

Product: Polyisocyanurate foam (with pentane)		Life cycle impact category			
Functional unit (F.U.) (kg): 0.68		Houston		Chicago	
Life cycle stage	Subcategory	Primary energy (MJ/FU)	GWP [kg CO ₂ e/FU]	Primary energy (MJ/FU)	GWP [kg CO ₂ e/FU]
Raw Material Acq.		-106.30	-4.34	-102.05	-4.17
Manufacturing		-0.53	-0.07	-0.51	-0.06
Installation and use	Installation	--	-0.36	--	-0.34
	Impacts avoided during use	9838	1497	14449	2561
Disposal		-0.09	-0.21	-0.08	-0.20
Transportation		-2.39	-0.06	-2.30	-0.06
Net Lifetime Impact		9728	1492	14344	2556

For the new building case, the indirect impact factors were orders of magnitude higher than the direct impact factors. This was expected to an extent, because the energy savings were calculated by comparing a code-level insulated building to an uninsulated building. For the existing building case, while still smaller, the direct impact factors contributed significantly to the total lifetime impact factors; 20-23% of the indirect factors in terms of primary energy consumption and 6-7% in terms of GWP.

Table 15 and Table 16 summarize the net lifetime impacts of all selected insulation materials for all the existing and new buildings, respectively, in all climate zones. Again, the data represent cases where both wall and roof insulation levels were upgraded to the current ASHRAE 90.1 requirements. For the scenarios considered here, polyisocyanurate (PIR) insulation performed the best in terms of both primary energy and GWP. Further, extruded polystyrene (XPS) had the lowest GWP impact factor, which, based on sign convention, indicated the highest negative environmental impact. The major reason for lower GWP impact factor for XPS are the fugitive emissions of blowing agents. It should be noted that the results in Table 15 and Table 16 are based on the assumption that HFC-152a is used in XPS; use of HFC-134a would have further lowered the GWP impact factor of XPS. The environmental impacts of aerogel, which can be considered a next-generation insulation material, were similar to those of foam insulation materials; within 10% for existing buildings and 0.35% for new buildings.

Table 15. Net lifetime environmental impact factors of the selected insulation materials in existing buildings.

Location	Building Type	Product	Net Lifetime Impact Factors		Indirect/Direct Impact Factors	
			Primary energy (MJ/FU)	GWP ₁₀₀ (kg CO ₂ e/FU)	Primary energy	GWP ₁₀₀
Houston	Medium Office	Polyisocyanurate	251.8	45.4	5	16
		Extruded polystyrene	213.8	35.3	3	4
		Expanded polystyrene	214.1	44.0	3	11
		Aerogel	206.9	39.7	3	6
	Standalone Retail	Polyisocyanurate	522.0	71.1	9	25
		Extruded polystyrene	484.0	60.9	6	6
		Expanded polystyrene	484.3	69.7	6	17
		Aerogel	477.1	65.4	5	9
Chicago	Medium Office	Polyisocyanurate	214.6	42.2	4	15
		Extruded polystyrene	176.7	32.0	3	3
		Expanded polystyrene	176.9	40.8	3	10
		Aerogel	169.8	36.5	3	5
	Standalone Retail	Polyisocyanurate	414.1	34.0	7	12
		Extruded polystyrene	376.1	23.9	5	3
		Expanded polystyrene	376.4	32.7	5	8
		Aerogel	369.2	28.3	4	4

Table 16. Net lifetime environmental impact factors of the selected insulation materials in new buildings

Location	Building Type	Product	Net Lifetime Impact Factors	Indirect/Direct Impact Factors
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			Primary energy (MJ/FU)	GWP ₁₀₀ (kg CO ₂ e/FU)	Primary energy	GWP ₁₀₀
Houston	Highrise Apartment	Polyisocyanurate	18,558	2,681	214	669
		Extruded polystyrene	18,507	2,668	135	153
		Expanded polystyrene	18,508	2,680	135	458
		Aerogel	18,498	2,674	127	230
	Medium Office	Polyisocyanurate	9,728	1,492	90	297
		Extruded polystyrene	9,665	1,475	57	68
		Expanded polystyrene	9,665	1,489	57	203
		Aerogel	9,653	1,482	53	102
	Standalone Retail	Polyisocyanurate	14,703	2,106	119	369
		Extruded polystyrene	14,631	2,087	75	84
		Expanded polystyrene	14,631	2,104	76	253
		Aerogel	14,618	2,096	71	127
Chicago	Highrise Apartment	Polyisocyanurate	19,910	2,858	241	748
		Extruded polystyrene	19,861	2,845	152	171
		Expanded polystyrene	19,862	2,856	152	512
		Aerogel	19,852	2,851	142	257
	Medium Office	Polyisocyanurate	14,344	2,556	138	530
		Extruded polystyrene	14,283	2,540	87	121
		Expanded polystyrene	14,284	2,554	87	363
		Aerogel	14,272	2,547	81	182
	Standalone Retail	Polyisocyanurate	17,568	2,377	146	427
		Extruded polystyrene	17,497	2,358	92	97
		Expanded polystyrene	17,497	2,374	92	292
		Aerogel	17,484	2,366	86	147

Finally, in Table 15 and Table 16, the ratios of indirect to direct impact factors are also listed. For the new buildings, where insulation upgrade meant increase from no insulation to 2013 code-level insulation, the energy savings and avoided emissions rendered the direct impacts insignificant. For new buildings, on average, the indirect impact factors were estimated to be two orders of magnitude greater than the direct impact factors; about 110 times for primary energy and 285 for GWP₁₀₀. For the existing buildings, however, with assumed insulation upgrades from 1989 to 2013 code-levels and remaining building lifetime of 30 years, the indirect and direct impact factors were comparable. However, even for existing buildings, the indirect impact factors were calculated to be about 5-10 times of the direct impact factors.

Overall, the indirect impacts were predominant, regardless of the insulation material. However, the fraction of direct impacts could become more significant with improvements in building construction and other energy efficiency-related upgrades. Measures such as reduced air infiltration through the building envelope, improved efficiency of heating and cooling

equipment, etc., can be expected to reduce the fraction of operational energy savings due to insulation alone and, hence, the indirect impact factors of insulation materials. Further, the results of the assessment for existing buildings highlight the issue of diminishing returns with increasing the amount of insulation. The embodied energy and related direct environmental impacts can be expected to increase linearly with increasing amounts of insulation, but the additional energy savings and indirect impacts will be smaller and smaller. There may be a point beyond which adding further insulation increases the direct impacts but has no effect on the indirect impacts.

3.4 Life Cycle Payback Analysis

Figure 8 shows the cumulative environmental impacts factors for polyisocyanurate insulation in existing medium office buildings in the two climate zones during the building lifetimes. The cumulative impact factors (X_{Cum}) were calculated as,

$$X_{Cum} = X_{Dir} + i \cdot \left(X_{Ind} / n \right) \quad (8)$$

In above equation, ' X_{Dir} ' and ' X_{Ind} ' are the direct and indirect impact factors (primary energy or GWP), ' i ' is the year number and ' n ' is the building lifetime in years (30 and 60 for existing and new buildings, respectively). The initial cumulative impact factors are negative, representing the embodied energy or direct impact factors, and increase over the years as the energy savings (indirect impacts) accumulate. The payback period is assumed to be the number of years (i) when the cumulative impact factor becomes zero or positive. The calculated payback periods for PIR insulation applied to medium office buildings in the two climate zones were 6-7 years for primary energy and about 2 years for GWP.

Table 17 lists the calculated payback periods for all the different insulation materials applied to the existing buildings in both climate zones. Consistent with results shown in the previous sections, the payback periods are shortest for PIR insulation. The payback periods are longest for aerogel for primary energy and XPS for GWP. The payback analysis for new building cases are not shown here since the indirect factors were orders of magnitude higher than the direct factors, resulting in payback periods of about 1 year or less.

Table 17. Life cycle payback analysis results for existing building cases

Location	Building Type	Product	Payback (years)	
			Primary energy	GWP ₁₀₀
Houston	Medium Office	PIR	6.2	1.9
		XPS	9.8	8.1
		EPS	9.7	2.7
		Aerogel	10.4	5.4
	Standalone Retail	PIR	3.3	1.2
		XPS	5.3	5.3
		EPS	5.3	1.8
		Aerogel	5.6	3.5
Chicago	Medium Office	PIR	7.0	2.0
		XPS	11.0	8.7
		EPS	11.0	2.9
		Aerogel	11.8	5.8
	Standalone Retail	PIR	4.1	2.4
		XPS	6.5	10.6
		EPS	6.4	3.5
		Aerogel	6.9	7.1

4. SUMMARY AND FUTURE WORK

This study represents one of the few systematic and standardized methods of calculating total lifetime environmental impacts of insulation materials. Specifically, the calculations of the avoided impacts during the ‘use’ phase of the insulation materials have been very clearly defined and are based on climate-specific standard building models. The direct impacts related to embodied energy of insulation materials as well as emission of blowing agents used in foam insulation were also calculated using existing data and a LCA software tool. The environmental impact factors were calculated for two categories: primary energy consumption and global warming potential in terms of equivalent carbon dioxide emissions.

Overall, the indirect impact factors dominated the net lifetime impacts (especially for new buildings) and, hence, there is a critical need for standardized calculation or determination methods of the indirect impact factors. For the existing building cases, the direct impact factors were also significant, as indicated by the ratio of indirect to direct impacts factors and the payback analysis. Further, if other energy-efficiency measures, in addition to the insulation upgrade, are considered, the direct impacts could become even more important and influence the decision-making. This article also highlights the lack of data for certain insulation materials and life cycle stages, a potential area for additional future work.

Finally, it is reiterated that the present calculations are not limited by practical considerations of suitability, or lack thereof, of insulation materials for a given building type. The goal was to compare insulation materials for identical applications. While selecting insulation materials, additional considerations of applicability, installation methods, durability, etc., are needed. Further, the environmental impacts of additional materials needed for installation, which may vary from one insulation material to another, should ideally also be considered.

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LIST OF FIGURES

Figure 1. Life-cycle diagram of environmental impact sources for insulation materials.

Figure 2. Direct environmental impacts of selected insulation materials (with 5% material loss rate) – primary energy consumption per functional unit.

Figure 3. Direct environmental impacts of selected insulation materials (with 5% material loss rate) – global warming potential (GWP₁₀₀) per functional unit.

Figure 4. Indirect environmental impacts – primary energy savings over 30 years for existing buildings.

Figure 5. Indirect environmental impacts – avoided CO₂ emissions over 30 years for existing buildings.

Figure 6. Indirect environmental impacts – primary energy savings over 60 years for new buildings.

Figure 7. Indirect environmental impacts – avoided CO₂ emissions over 60 years for new buildings.

Figure 8. Cumulative environmental impacts (primary energy and GWP) of polyisocyanurate insulation in existing medium office buildings during the building lifetime.

Figure 9. Life-cycle diagram of environmental impact sources for insulation materials.

Figure 10. Direct environmental impacts of selected insulation materials (with 5% material loss rate) – primary energy consumption per functional unit.

Figure 11. Direct environmental impacts of selected insulation materials (with 5% material loss rate) – global warming potential (GWP₁₀₀) per functional unit.

Figure 12. Indirect environmental impacts – primary energy savings over 30 years for existing buildings.

Figure 13. Indirect environmental impacts – avoided CO₂ emissions over 30 years for existing buildings.

Figure 14. Indirect environmental impacts – primary energy savings over 60 years for new buildings.

Figure 15. Indirect environmental impacts – avoided CO₂ emissions over 60 years for new buildings.

Figure 16. Cumulative environmental impacts (primary energy and GWP) of polyisocyanurate insulation in existing medium office buildings during the building lifetime.