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Lifetime Energy and Environmental Impacts of Insulation Materials in commercial Building Applications – Assessment Methodology and Sample Calculations

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I. Executive Summary

Application of insulation materials to building envelopes is a relatively easy and effective way of reducing energy consumption for space conditioning and, consequently, limiting the negative environmental impacts from the buildings sector. While insulation materials have a positive impact on the environment by reducing energy consumption in buildings, they also have some negative environmental 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 environmental impacts avoided due to the reduced building energy consumption. It is important to identify insulation materials for buildings that will result in minimum negative environmental impacts.

The objective of this project was to perform an assessment of the lifetime energy and environmental impacts of building insulation materials based on a previously developed protocol. The developed protocol was used for calculating the lifetime environmental impacts of selected insulation materials. Two Excel-based tools were developed: 1) to calculate embodied energy and GWP (equivalent CO_2 emissions) of insulation materials, and 2) to estimate energy savings and avoided environmental impacts due to the use of insulation materials in buildings. The direct environmental impacts were estimated using data from existing literature and life cycle analysis software; the indirect impacts were based on simulations of prototype whole-building models.

This report summarizes the simulation study based on the recommendations of a previously developed protocol (A protocol for lifetime energy and environmental impact assessment of building insulation materials) by Shrestha et al., 2014. It also discusses a simplified algorithm based technique developed to quantify energy savings potential without requiring whole-building energy simulations. The report 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. Estimating the energy savings impact of insulation materials for the buildings in United States was an important aspect of this recommendation and comparative analyses of selected insulation materials were performed.

Conclusions

The developed protocol was used for calculating the lifetime environmental impacts of selected insulation materials. Two Excel-based tools were developed: 1) to calculate embodied energy and GWP (equivalent CO2 emissions) of insulation materials, and 2) to estimate energy savings and avoided environmental impacts due to the use of insulation materials in buildings. The direct environmental impacts were estimated using data from existing literature and life cycle analysis software; the indirect impacts were based on simulations of prototype whole-building models.

To assess the 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 life cycle assessment (LCA) software.[1] SimaPro is an LCA software 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) (2010), the U.S.-EI Database (2011) and the U.S. LCI Database (2012) - 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 and greenhouse gas (GHG) emissions from the five key phases in the life cycle of insulation products.

To calculate the indirect energy and environmental impact (use phase) of the insulation materials a simple regression based spreadsheet was developed. The regression tool was based on the simulation study carried out to estimate the energy savings potential of insulation upgrades of 16 different commercial buildings in 15 climatic locations in the United States (US). These buildings represent the majority of commercial buildings types in the US. Once the simulation results were collected for all the cases, the simplified equations for determining heating and cooling energy savings based on the annual cooling degree days (CDD), heating degree days (HDD), wind speed, wind direction and solar radiation as independent variable were developed for each building type considered in this analysis. After analyzing several combinations of independent input variables, it was determined that CDD or HDD, direct normal solar (DS) and diffuse solar (DIFF) irradiance would produce the best set of equations for most building types. The objective was to develop a simple Excel based tool that can be used to estimate the electricity and gas savings due to insulation upgrades by providing only a few parameters i.e. the building type, floor area, heating degree days, cooling degrees days, direct normal and diffuse solar radiation.

The assessment protocol was applied to certain commercial building types with selected insulation materials. For new construction, 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 GWP_{100}. For the existing construction cases, with assumed insulation upgrades from 1989 to 2013 code-levels and remaining building lifetime of 30 years, the indirect impacts were not as high. However, even for existing construction, the indirect impact factors were calculated to be about 5-10 times of the direct impact factors.

Overall, for both new and existing construction, the indirect impacts were predominant, regardless of the insulation material. However, the 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 operational energy savings due to insulation alone and, hence, the indirect impact factors of insulation materials. Further, the results of the assessment for existing construction highlight the issue of diminishing returns with increasing

[1] http://www.pre-sustainability.com/simapro

the amount of insulation in walls and roofs beyond a certain level. 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 greater than the decrease in the indirect impacts, resulting net negative environmental impact.

II. Introduction

According to the United States (U.S.) Energy Information Administration (EIA), in 2012, commercial buildings consumed 17.6 quadrillion Btu (quad) of primary energy, which was 19% of the total U.S. primary energy consumption [USDOE, 2014]. The primary energy consumption in the commercial sector is projected to increase by 3.3 quads from 2012 to 2040, the second largest increase after the industrial sector [USDOE, 2014]. Further, space heating and cooling accounted for 29% of the delivered (or site) energy consumption in commercial buildings [USDOE, 2014]. Reducing energy consumption in buildings 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 in buildings. 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) [Harvey, 2007].

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.

Shrestha et al. 2014 proposed an assessment protocol for the lifetime environmental impacts of insulation materials in terms of primary energy consumption and global warming potential. The aim of the assessment protocol was to identify all factors that contribute to the total energy consumption and environmental impacts of different insulation products. 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. In addition, the protocol also proposed standard calculation methodologies for estimating the avoided environmental impacts associated with the reduced operational energy of buildings due to the use of insulation materials.

This report presents the results of the aforementioned assessment protocol applied to certain commercial building types with selected insulation materials. The assessment 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 LCA software. The indirect impact factors were calculated based on simulations of standard prototype whole-building models. Complete details of the protocol have been provided by Shrestha et al. 2014, but for convenience, the important and relevant details have also been repeated in this report.

It should be noted that the sample 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 construction. This report is also not intended to be used as a recommendation for using one insulation material over another based purely on the current results; rather this report emphasizes on the demonstration of the calculation of lifetime environmental impact factors of a set of insulation materials for a given set of scenarios (building type and climate zone). While selecting insulation materials for particular applications, additional considerations of applicability, installation methods, durability, etc., are needed.

III. Project Scope

Opaque envelope building insulation has been largely driven by code with little attention paid to the lifetime energy and 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 life-cycle climate impacts. However, adoption has been limited due to (1) general lack of awareness and (2) uncertainty about the relative costs and benefits of the latest generation of insulation products vs. traditional products. This project will address these challenges by (1) quantifying the lifetime environmental and energy impacts of different types of insulation products using the protocol developed earlier, (2) disseminating this information through strategic deployment channels including CBEA, and (3) encouraging adoption of advanced insulation products that provide greater energy savings so that building owners, managers and developers can make more informed choices. It can be expected that this will help boost the owners' confidence in new construction and retrofit measures using advanced insulation materials that lead to greater energy efficiency.

IV. Project Approach

ORNL developed a protocol to perform assessment of lifetime energy savings potential, embodied energy, and environmental and energy impact of different types of insulation products. The protocol has been published in peer-reviewed journal "Environmental Impact Assessment Review".

This project quantified the energy savings potential and associated environmental impacts (benefits) of traditional and advanced insulation products over their life time when used in different types of buildings, such as supermarket, office, warehouse, school, restaurant, etc., located in various climate conditions. The study also included new construction and retrofit applications.

Using the protocol developed by ORNL, the study also quantified the embodied energy, emission of gases with global warming potential during the life of insulation products and their environmental impact. This methodology will allow quantifying lifetime energy and environmental impact of different insulation products.

VI. Lifetime Impact Assessment Methodology

The review of current state of assessment methodologies (Shrestha et al, 2014) suggested 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 was 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 were also 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 proposed 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.

The methodology is based on the protocol ("A protocol for lifetime energy and environmental impact assessment of building insulation materials") defined by Shrestha et al., 2014. Relevant details of the assessment methodology are described here:

Functional Unit

Most environmental product declarations (EPD) and life cycle assessments (LCA) use functional units as the basis for the environmental impact assessment results. Following Shrestha et al. 2014, the functional unit for this assessment was defined as mass (kg) of insulation material needed to cover a 1 m^2 area at a thickness providing an average thermal resistance (RSI) of 1 $m^2 \cdot K/W$ 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 $m^2 \cdot K/W$), λ is the thermal conductivity (W/m·K), ρ is the density (kg/m^3), and A is a unit area (1 m^2). Alternatively, the functional unit can be defined in inch-pound (IP) units as the mass (lb) of insulation material covering an area of 10.76 ft^2 at a thickness that provides an average thermal resistance (RIP) of 5.67 $h \cdot ft^2 \cdot {}^{\circ}F/Btu$ over 60 years, which makes the FU unit system-independent (i.e., 1 FU_{SI} = 1 FU_{IP}).

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:

- Primary or source energy in megajoules (MJ) per functional unit.
- Global warming potential (GWP_{100}) in kilograms carbon dioxide (CO_2) equivalent (kg CO_2e) per functional unit.

Following Shrestha et al., 2014 the calculated impact factors were 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.

The key stages in the life cycle of insulation materials are raw material acquisition, manufacturing, installation and use, disposal, and transportation. These terms are further defined below. For products using foam blowing agents during manufacturing or installation, environmental impacts associated with the manufacturing of the blowing agent were included under the raw material acquisition phase. Also included were fugitive emissions of high-GWP gases that occur during the manufacturing of the blowing agent as well as during the other life cycle phases of foam-based insulation materials.

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 accounted 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 EnergyPlus[2] simulations of standard prototype building models.

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 occurred, this life cycle phase also accounted 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 global warming potential. Per Shrestha at al. (2014), a 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. It was assumed that 100% of the blowing agent used in foam insulation material was eventually emitted to the atmosphere; no recovery at end-of-life was assumed.

[2] http://apps1.eere.energy.gov/buildings/energyplus/

A. Direct Environmental Impact assessment

To assess the direct environmental impacts of the insulation materials, life cycle data were collected from publicly available resources, including published literature and industry sources. Under the direct environmental impacts, all life cycle stages and subcategories listed in Table 1 are included except 'Avoided impacts during use phase'.

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

Table 2 and Table 3 list the direct environmental impact factors of the selected insulation materials in terms of primary energy consumption and GWP_{100} for the different life cycle stages. Following the sign convention stated in section 2.2, all direct environmental impacts are negative. In Table 2, the impact factors have been modified to account for an assumed 5% insulation loss rate, according to eq. (2). The insulation loss rates can be expected to be different for different insulation materials and applications. The primary energy consumption and GWP_{100} values should be modified appropriately if accurate loss rate data are available. In Table 3, the impact factors have been modified to account for the 5% loss rate and a single replacement during the building lifetime. In commercial buildings, it is common to replace the roof insulation whenever any repairs to the roof are performed, usually at 20-30 years of the building lifetime. As illustrative examples, the impact factors from Table 2 are presented graphically in Figure 1 and Figure 2.

Table 2. Direct environmental impact factors of selected insulation materials with assumed 5% loss rate

	Polyiso (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	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**
GWP_{100} (kg CO_2e per Functional Unit)				
Raw material acquisition	-2.59	-3.59	-3.32	--
Manufacturing	-0.04	-2.52	-0.86	-8.43
Installation	-0.21	-3.94	-0.04	Neg.
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 3. Direct environmental impact factors of selected insulation materials with assumed 5% loss rate and single replacement during building lifetime

	Polyiso (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	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**
GWP_{100} (kg CO_2e per Functional Unit)				
Raw material acquisition	-5.17	-7.17	-6.64	--
Manufacturing	-0.08	-5.04	-1.71	-16.86
Installation	-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**

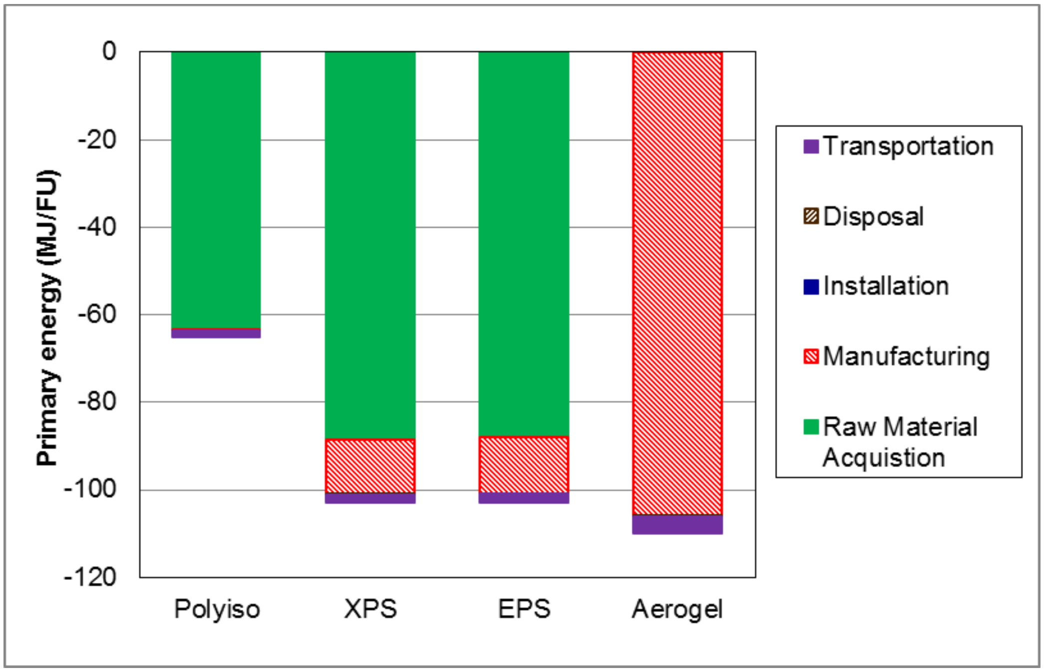


Figure 1. Direct environmental impacts of selected insulation materials (with 5% loss rate) – primary energy consumption per functional unit.

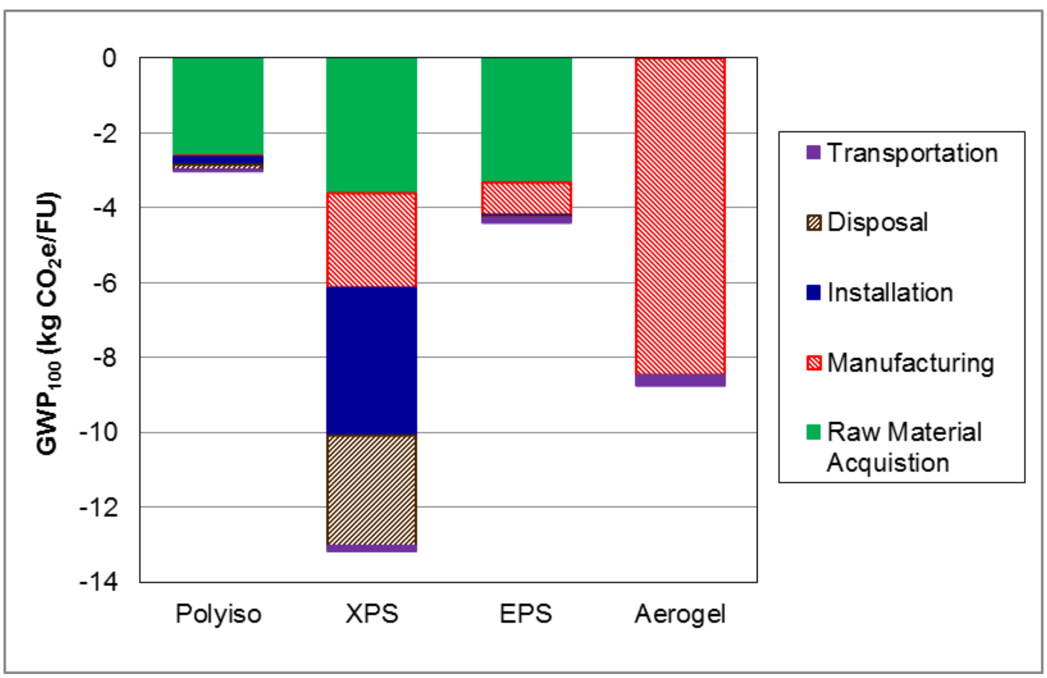


Figure 2. Direct environmental impacts of selected insulation materials (with 5% loss rate) – global warming potential (GWP_{100}) per functional unit.

The SimaPro LCA software was primarily used to generate data for polyiso insulation. SimaPro was also used as the primary source of information for both XPS and EPS. Due to lack of availability of disposal-related data for XPS and EPS, proxy data from another insulation material were used. Transportation related data were obtained from a report by Polyisocyanurate Insulation Manufacturers Association and were applied to all insulation materials. Data for aerogel were obtained from the literature. For aerogel, data related to raw material acquisition were not available and have not been presented; it is not known if any energy consumption or emissions related to raw material acquisition were already considered within the manufacturing step. Primary energy consumption related to installation was deemed to be negligible (Neg.) compared to the other life cycle stages. The GWP100 for foam insulation materials during installation is due to fugitive emissions and is assumed to be zero for aerogel.

A 100-year GWP was used to calculate impact factors associated with fugitive emissions of the blowing agents used in foam insulation materials. 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. GWP_{100} can be used to convert the mass of blowing agents into equivalent mass of CO2 (kg CO_2e). For example, 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 loss rate assumptions from Intergovernmental Panel on Climate Change (IPCC) and Technology and Economic Assessment Panel (TEAP) reports. Table 2 and Table 3 indicate that polyiso has the lowest primary energy consumption on a per functional unit basis, followed by XPS and EPS, 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 2 and Table 3) and HFC-134a. Table 4 lists the relative contributions of the fugitive emissions of the different blowing agents (assuming no loss of insulation or replacement). It is evident that the higher GWP blowing agents significantly increase the total GWP_{100} of the insulation materials.

Table 4. Effect of blowing agents and fugitive emissions on total GWP of foam insulation materials

	Polyiso	XPS (HFC-134a)	XPS (HFC-152a)	EPS
Fugitive emissions (kg CO_2e)	-0.34	-92.06	-8.33	-0.09
Total GWP_{100} (kg CO_2e)	-2.85	-101.11	-12.50	-4.17
% kg CO_2e due to fugitive emissions	**11.79**	**91.06**	**66.64**	**2.26**

Since the direct impact factors are dependent on loss rates and replacement, for a building with wall and roof insulation, the effective impact factors need to be calculated as a weighted average of the respective impact factors of the wall and roof insulation. The number of functional units (N) for the walls and roofs of each building type can be calculated as,

$$N = (R_{Env} \cdot \lambda \cdot \rho \cdot A_{Env}) / FU \qquad (2)$$

R_{Env} and A_{Env} are the prescribed thermal resistance ($m^2 \cdot K/W$) and area (m^2) of the different envelope components.

Table 5 lists the functional units of the insulation materials following eq. (1) and using data from literature. Table 6 lists the number of functional units (N) for the different building types in the two climate zones, calculated according to eq. (2). Since the functional unit is a normalized unit representing the amount of insulation providing 1 $m^2 \cdot K/W$ over a unit area, 'N' is independent of the insulation material type.

Table 5. Functional units of the selected insulation materials

Insulation	Thermal conductivity (W/m·K)	Density (kg/m3)	Functional Unit (kg)
Polyiso	0.0236	29	0.68
XPS	0.0320	30	0.96
EPS	0.0360	25	0.90
Aerogel	0.0130	144	1.87

Table 6. Number of functional units for the different building types and climate zones

Location	New construction		Existing construction	
	Wall	Roof	Wall	Roof
		Highrise apartment		
2A (Houston)	6,585	3,381	--	--
5A (Chicago)	10,862	4,154	--	--
		Medium office		
2A (Houston)	3,378	7,166	1,916	3,182
5A (Chicago)	5,573	8,803	2,159	3,641
		Standalone retail		
2A (Houston)	995	9,898	891	4,395
5A (Chicago)	1,928	12,160	352	5,030

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

$$X_{Eff} = \frac{(X_{Wall} \cdot N_{Wall} + X_{Roof} \cdot N_{Roof})}{(N_{Wall} + N_{Roof})} \qquad (3)$$

'X_{Eff}' is either the primary energy consumption (MJ/FU) or GWP_{100} (kg CO_2e/FU).

Table 7 and Table 8 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 walls and roofs insulated according to 2013 ASHRAE 90.1 for new construction and upgraded to 2013 code requirements from 1989 code requirements for existing construction. There is no 'highrise apartment' case for existing construction as the prototype building model for this type was only added in the recent version of prototype buildings, applicable to new construction only.

Table 7. Direct environmental impact factors on a per functional unit basis for new construction

Location	Building Type	Product	Direct Lifetime Impact Factors	
			Primary energy (MJ/FU)	GWP_{100} [kg CO_2e/FU]
Houston	Highrise Apartment	Polyiso	-87.2	-4.0
		XPS	-138.0	-17.6
		EPS	-137.7	-5.9
		Aerogel	-147.3	-11.7
	Medium Office	Polyiso	-109.3	-5.0
		XPS	-173.0	-22.1
		EPS	-172.7	-7.4
		Aerogel	-184.7	-14.6
	Standalone Retail	Polyiso	-124.2	-5.7
		XPS	-196.6	-25.1
		EPS	-196.2	-8.4
		Aerogel	-209.9	-16.6
Chicago	Highrise Apartment	Polyiso	-83.1	-3.8
		XPS	-131.5	-16.8
		EPS	-131.2	-5.6
		Aerogel	-140.4	-11.1
	Medium Office	Polyiso	-104.9	-4.8
		XPS	-166.1	-21.2
		EPS	-165.8	-7.1
		Aerogel	-177.3	-14.0
	Standalone Retail	Polyiso	-121.3	-5.6
		XPS	-192.0	-24.5
		EPS	-191.5	-8.2
		Aerogel	-204.9	-16.2

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

Location	Building Type	Product	Direct Lifetime Impact Factors	
			Primary energy (MJ/FU)	GWP_{100} [kg CO_2e/FU]
Houston	Medium Office	Polyiso	-65.1	-3.0
		XPS	-103.0	-13.1
		EPS	-102.8	-4.4
		Aerogel	-110.0	-8.7
	Standalone Retail	Polyiso	-65.1	-3.0
		XPS	-103.0	-13.1
		EPS	-102.8	-4.4
		Aerogel	-110.0	-8.7
Chicago	Medium Office	Polyiso	-65.1	-3.0
		XPS	-103.0	-13.1
		EPS	-102.8	-4.4
		Aerogel	-110.0	-8.7
	Standalone Retail	Polyiso	-65.1	-3.0
		XPS	-103.0	-13.1
		EPS	-102.8	-4.4
		Aerogel	-110.0	-8.7

B. Indirect Environmental Impact assessment

Building insulation materials are primarily used to reduce the energy consumption for maintaining comfortable indoor conditions. To this end, insulation materials increase the resistance (R-value) to heat flow through the building envelope (walls, roof, foundation, etc.), which then diminishes heat flow between conditioned and unconditioned spaces and thereby reduces the amount of energy required by building heating, ventilation, and air-conditioning (HVAC) systems to maintain thermal comfort. The primary energy saved, and hence CO_2 emissions avoided, over the building service life are the indirect environmental impacts of the insulation materials. The indirect impacts associated with the operational energy of buildings usually dominate the total lifetime environmental impacts, often exceeding the direct impacts by orders of magnitude.

The indirect environmental impact factors are usually calculated using correlations, analytical models or whole building energy models. Different LCAs use customized building models, and there appears to be no standardized set of modeling parameters. Furthermore, the energy saved and environmental impact avoided over the lifetime of the insulation material depends on geographical location, climate, building characteristics, and use. A simplified spreadsheet based tool was developed in this project to calculate the site-energy savings with applications of 2013 ASHRAE 90.1 code-level insulation for different commercial building types in different climate locations. The indirect impact factors of avoided primary energy generation and CO_2 emissions can be estimated from the site-energy savings using appropriate regional or national conversion factors.

The methodology to develop the tool is given in the following section:

B1. Simulation Study

The simulation study was carried out to estimate the energy savings potential of insulation upgrades of 16 different commercial buildings in 15 climatic locations in the United States (US). These buildings represent the majority of commercial buildings types in the US and the nationwide impact will be estimated by using the weighting factors for construction volume of various building types at different locations.

The 16 prototype building models considered were based on the DOE prototype commercial building models for Post-1980 and New construction[3] (Deru et al. 2010, Goel et al. 2014). Two sets of buildings were selected for this study. The first set consisted of existing buildings built according to ASHRAE 90.1-1989 code and the second set represented the new construction based on ASHRAE 90.1-2013 code. The models used for new construction were significantly enhanced from the existing prototype models by PNNL (Goel et al., 2014). The following sets of building models for each of the 16 building type were created in this study to represent the baseline case and cases with insulation upgrades for 15 climatic locations:

1. Existing construction (retrofit application)
   a. Baseline case - ASHRAE 90.1-1989 code compliant
   b. Upgraded wall insulation – modified wall insulation to ASHRAE 90.1-2013 code compliant wall insulation
   c. Upgraded roof insulation – modified roof insulation to ASHRAE 90.1-2013 code compliant roof insulation
   d. Upgraded wall and roof insulation – modified wall and roof insulation to ASHRAE 90.1-2013 code compliant wall and roof insulation

2. New construction
   a. Baseline case - No wall or roof insulation
   b. Upgraded wall insulation – modified wall insulation to ASHRAE 90.1-2013 code compliant wall insulation
   c. Upgraded roof insulation – modified roof insulation to ASHRAE 90.1-2013 code compliant roof insulation
   d. Upgraded wall and roof insulation – modified wall and roof insulation to ASHRAE 90.1-2013 code compliant wall and roof insulation

The reason for dividing the simulation study into two separate categories, i.e. existing and new

[3] Commercial Prototype Building Models : http://www.energycodes.gov/commercial-prototype-building-models

construction was to cover the cases with no insulation and with insulation as prescribed by ASHRAE1989. The 'existing construction' case pertains to retrofitting an existing building constructed after 1980 (ASHRAE 90.1-1989 code complaint building) and adding insulation to walls and roofs as per the requirements of ASHRAE 90.1-2013. The existing construction cases assumed that the building received only an envelope retrofit and all other buildings characteristics and equipment, lighting and HVAC, etc. were not changed/upgraded.

'New construction' pertains to adding insulation to a building with no wall or roof insulation but with all other buildings characteristics (equipment, lighting, HVAC, etc.) as per the ASHRAE 90.1-2013 code. The added wall and roof insulation were as per the requirements of ASHRAE 90.1-2013. These two categories/scenarios are assumed to cover the extreme cases of retrofitting scenarios. This was done to avoid having to simulate all the possible permutations and combinations of various retrofitting measures in buildings. Various cases include the scenarios such as what if only wall is retrofitted or just roof or both.

In both existing and new construction models, all parameters except the envelope were maintained at code compliant levels, as per the 1989 and 2013 versions of ASHRAE 90.1 for existing and new construction, for the baseline and upgraded insulation cases. The wall and roof insulation values varied depending on the building type and climatic location.

Prototype EnergyPlus models for post-1980 and new construction were used for the existing and new buildings, respectively. Besides 240 baseline prototype models of existing and new construction each (16 building types x 15 climatic locations), overall modified Energy plus model sets for this simulation study consisted of 720 (16 building types x 15 climatic locations x 3 upgraded insulation case) models for existing construction and 720 models for new construction i.e. a total of 1,920 (2 x 720 + 2 x 240) EnergyPlus models. Table 9 shows the number of models for each case described above.

Table 9 : Number of models used for the analysis

Model Description	Number of models
Existing construction	
Baseline case - ASHRAE 90.1-1989 code compliant	240
Upgraded wall insulation (ASHRAE 90.1-2013 compliant wall)	240
Upgraded roof insulation (ASHRAE 90.1-2013 compliant roof)	240
Upgraded wall and roof insulation (ASHRAE 90.1-2013 compliant wall and roof)	240
New construction	
Baseline case - No wall and roof insulation	240
Upgraded wall insulation (ASHRAE 90.1-2013 compliant wall)	240
Upgraded roof insulation (ASHRAE 90.1-2013 compliant roof)	240
Upgraded wall and roof insulation (ASHRAE 90.1-2013 compliant wall and roof)	240
Total	1,920

The wall and roof constructions varied by building type and the insulation levels varied by climate locations. Table 10 shows the building types, area, and roof and wall construction for existing and new construction.

Table 9 : Building types and envelope characteristics

Building Type	Floor area (ft^2)	Number of floors	Existing construction		New construction	
			Roof	Wall	Attic and other	Wall
Small Office	5,500	1	Attic and other	Mass	Attic and other	Wood frame
Medium Office	53,628	3	IEAD	Steel frame	IEAD	Steel frame
Large Office	498,588	12	IEAD	Mass	IEAD	Mass
Mid-rise Apartment	33,740	4	IEAD	Steel frame	IEAD	Steel frame
High-rise Apartment*	75,990	10			IEAD	Steel frame
Quick Service Restaurant	2,500	1	Attic and other	Wood frame	Attic and other	Wood frame
Full Service Restaurant	5,500	1	Attic and other	Steel frame	Attic and other	Steel frame
Hospital	241,351	5	IEAD	Mass	IEAD	Mass
Outpatient Healthcare	40,946	3	IEAD	Steel frame	IEAD	Steel frame
Small Hotel	43,200	4	Attic and other	Steel frame	IEAD	Steel frame
Large Hotel	122,120	6	IEAD	Mass	IEAD	Mass
Primary School	73,960	1	IEAD	Steel frame	IEAD	Steel frame
Secondary School	210,887	2	IEAD	Steel frame	IEAD	Steel frame
Stand-Alone Retail	24,962	1	IEAD	Mass	IEAD	Mass
Strip Mall	22,500	1	IEAD	Steel frame	IEAD	Steel frame
Supermarket*	45,000	1	IEAD	Mass		
Warehouse	52,045	1	Metal building roof	Metal building	Metal building roof	Metal building

Note: IEAD- Insulation entirely above deck; High-rise apartment and supermarket exist only in new and old construction respectively. *:High-rise Apartment and Supermarket building type models are available only in new and existing constructions respectively.

The simulations were carried out for 15 locations in different ASHRAE climate zones. The locations along with the cooling degree days (CDD) and heating degree days (HDD)[4] at base temperature of 65°F are given in Table 11.

Table 10: Climatic locations used for the simulations

Location	Climate Zone	CDD	HDD
Miami	1A	4,459	130
Houston	2A	3,001	1,415
Phoenix	2B	4,558	941
Memphis	3A	2,214	2,936
El Paso	3B	2,315	2,466
San Francisco	3C	142	2,707
Baltimore	4A	1,228	4,567
Albuquerque	4B	1,348	4,070
Salem	4C	292	4,576
Chicago	5A	842	6,311
Boise	5B	889	5,657
Burlington	6A	497	7,405
Helena	6B	374	7,679
Duluth	7	209	9,425
Fairbanks	8	70	13,529

For new construction, the EnergyPlus models, except the base case which assumed no wall or roof insulation, assumed the minimum wall and roof insulation values required as per ASHRAE 90.1-2013. To meet the minimum envelope code requirements, ASHRAE 90.1-2013 allows both assembly maximum U factor and minimum insulation R-value. To calculate the insulation R-value for the models, PNNL used the U-factor method together with the assemblies described in Appendix A of ASHRAE 90.1-2013. The insulation layer R-value is calculated by subtracting the R-value of individual layers, including the thermal resistance of interior (R-0.61 Roof, R-0.68 Walls)) and exterior (R-0.17) air films, from the inverse of the U-factor. For new construction, the insulation R-value of wall and roof construction used in the models for different building type and climatic locations are given in Table 12.

[4] Definition: http://www.erh.noaa.gov/cle/climate/info/degreedays.html

Table 11 : Wall and roof insulation R-values for new construction building models

Location	Climate Zone	Wall insulation R-Value (hr °F ft²/Btu)				Roof insulation R-Value (hr °F ft²/Btu)		
		Mass	Metal Building	Steel Framed	Wood Framed and other	IEAD	Metal Building	Attic and other
Miami	1A	NR	9.5	5.9	9.1	19.7	23.6	35.4
Houston	2A	4.8	9.5	9.7	9.1	24.5	24.9	35.4
Phoenix	2B	4.8	9.5	9.7	9.1	24.5	24.9	35.4
Memphis	3A	6.3	9.5	10.8	9.1	24.5	24.9	35.4
El Paso	3B	6.3	9.5	10.8	9.1	24.5	24.9	35.4
San Francisco	3C	6.3	9.5	10.8	9.1	24.5	24.9	35.4
Baltimore	4A	7.8	15.4	13.4	13.4	30.1	26.2	46.0
Albuquerque	4B	7.8	15.4	13.4	13.4	30.1	26.2	46.0
Salem	4C	7.8	15.4	13.4	13.4	30.1	26.2	46.0
Chicago	5A	9.3	18.7	16.0	17.4	30.1	26.2	46.0
Boise	5B	9.3	18.7	16.0	17.4	30.1	26.2	46.0
Burlington	6A	10.7	18.7	18.2	17.4	30.1	31.5	46.0
Helena	6B	10.7	18.7	18.2	17.4	30.1	31.5	46.0
Duluth	7	12.3	21.4	18.2	17.4	34.6	33.7	57.2
Fairbanks	8	19.0	24.3	24.8	29.1	34.6	37.7	57.2

For existing construction, the EnergyPlus models assumed the minimum wall and roof insulation values required as per ASHRAE 90.1 1989. To meet the minimum envelope code requirements, ASHRAE 90.1-1989 allows only maximum assembly U factors. The insulation thicknesses were calculated based on this U-factor requirement. The procedure to determine wall and roof U-Factors as per ASHRAE 90.1-1989 is given in the following section:

B1.1. Estimation of Wall and Roof U-Factors for ASHRAE 90.1-1989

Wall and roof U-Factors were required for the fifteen cities listed in Table 11. These cities are listed again in Table 13 along with the equivalent climate zone specification, as per ASHRAE 90.1-1989 classification. ASHRAE 90.1-1989 has a fairly complicated procedure for estimating the required U-Factors for wall and roof assemblies. The Alternative Component Package Method was employed for this project.

Table 12 : Climatic location mapping to ASHRAE 90.1-1989 zones

Climate Zone	City	ASHRAE 90.1-1989 Alternate Component Package
1A	Miami, FL	8A-15
2A	Houston, TX	8A-10
2B	Phoenix, AZ	8A-18
3A	Memphis, TN	8A-24 (used Atlanta)
3B	El Paso, TX	8A-12 (used Las Vegas)
3C	San Francisco, CA	8A-5
4A	Baltimore, MD	8A-25
4B	Albuquerque, NM	8A-23
4C	Salem, OR	8A-19
5A	Chicago, IL	8A-26
5B	Boise, ID	8A-28
6A	Burlington, VT	8A-33
6B	Helena, MT	8A-32
7	Duluth, MN	8A-36
8	Fairbanks, AZ	8A-38

The Alternative Component Package Method divides the United States into 38 different climate zones and U-Factor requirements for each zone are detailed in Tables 8A-1 through 8A-38 of ASHRAE 90.1-1989. The tables list representative cities, e.g. Table 8A-1 lists Barbers Point, Hilo, Honolulu, and Lihue HI as the representative cities. The tables that were used to represent these cities are also listed in the table above. Each table lists unique U-Factors for lightweight wall systems and roof assemblies. However, the mass wall systems have a variety of required maximum U-Factors based on fenestration area, internal loadings, and the wall mass. Table 8-1 of ASHRAE 90.1-1989, with assumed internal loads for shell and speculative buildings, was used to estimate the internal loads for the current study. Fenestration areas were assumed to be 30 percent or less, and the heat capacity (HC) of the wall was assumed to be between 10-15 Btu/ft^2 °F. Based on these assumptions, the U-Factors of mass walls were estimated for both insulation systems applied to the interior and exterior of the wall mass. The target U-Factors for each wall and roof system based on climate zone are summarized in Table 14 .

Table 13: Target U-Factors for wall and roof systems for climate zones 1A to 8.

Climate Zone	U-Factor, Btu/(hr ft^2 °F) for Zone							
	Roof			Wall				
	Attic	IEAD	Metal	Mass Interior	Mass Exterior	Steel	Wood	Metal
1A	0.074	0.074	0.074	1	1	1	1	1
2A	0.066	0.066	0.066	0.25	0.36	0.15	0.15	0.15
2B	0.046	0.046	0.046	0.35	0.41	0.24	0.24	0.24
3A	0.057	0.057	0.057	0.15	0.2	0.12	0.12	0.12
3B	0.058	0.058	0.058	0.22	0.31	0.15	0.15	0.15
3C	0.088	0.088	0.088	0.37	0.47	0.13	0.13	0.13
4A	0.058	0.058	0.058	0.11	0.15	0.089	0.089	0.089
4B	0.059	0.059	0.059	0.16	0.23	0.1	0.1	0.1
4C	0.064	0.064	0.064	0.09	0.11	0.092	0.092	0.092
5A	0.053	0.053	0.053	0.094	0.13	0.082	0.082	0.082
5B	0.051	0.051	0.051	0.12	0.18	0.082	0.082	0.082
6A	0.045	0.045	0.045	0.066	0.076	0.065	0.065	0.065
6B	0.049	0.049	0.049	0.075	0.09	0.072	0.072	0.072
7	0.04	0.04	0.04	0.058	0.065	0.058	0.058	0.058
8	0.031	0.031	0.031	0.046	0.051	0.045	0.045	0.045

B1.1.2. Construction of Basic Walls and Roofs

Basic constructions for the walls and roofs were taken from ASHRAE 90.1-1989. There were three basic constructions for roof assemblies. The attic construction was comprised of, from the interior side of the assembly, an interior air film, 0.5 inch thick gypsum board, an insulation layer of fiberglass loose fill, another 0.5 inch thick gypsum board, and an outside air film. For the insulation entirely above deck (IEAD) construction, an interior air film, metal deck, an insulation layer of polyisocyanurate foam, a roof membrane, and an outside air film was used. For the metal construction, an interior air film, an insulation layer of fiberglass batt, a metal roof, and an outside air film were employed.

There were five basic wall constructions. The mass wall with interior insulation was comprised of an interior air film, 0.5 inch thick gypsum board, a 3.5 inch fiberglass batt insulation layer thermally shorted with steel framing, an 8 inch heavyweight concrete layer, 1 inch of stucco, and an outside air film. The mass wall with exterior insulation was comprised of an interior air film, 0.5 inch thick gypsum board, an 8 inch heavyweight concrete layer, polyisocyanurate foam insulation, 1 inch of stucco, and an outside air film. The steel wall included an interior air film, 0.5 inch thick gypsum board, a 3.5 inch fiberglass batt insulation layer thermally shorted with steel framing, wood siding, and an outside air film. The wood wall was comprised of an interior air film, 0.5 inch thick gypsum board, a 3.5 inch fiberglass batt insulation layer thermally shorted with wood framing, wood siding, and an outside air film. The metal wall was made up of an interior air film, 0.5 inch thick gypsum board, and fiberglass batt insulation layer thermally shorted with steel purlins, metal siding, and an outside air film.

With the exception of polyisocyanurate foam and loose fill fiberglass, all material property data were retrieved from the ASHRAE Handbook of Fundamentals, Chapter 18 (ASHRAE HOF, 2012) on Nonresidential Cooling and Heating Load Calculations, Table 18 and are summarized in Table 15. Data for polyisocyanurate foam and loose fill fiberglass was obtained from manufacturer's data sheets. In addition, data related to the impact of the thermal bridging of metal and wood studs on cavity insulation were obtained from Tables A9.2-2 and A9.4-2 of ASHRAE 90.1-2013.

Table 14: Material properties data (Source: ASHRAE HOF, 2012)

Material	R-value, (hr ft^2 °F)/Btu
Inside Air Film (Heat Flow Vertical)	0.92
Outside Air Film (Heat Flow Vertical)	0.25
0.5 inch Gypsum Board	0.45
Metal Deck	0.00
Metal Roof	0.00
Roof Membrane	0.33
1 inch Polyisocyanurate Foam	6.00
3.5 inch Fiberglass Batt Insulation	11.00
1 inch Attic Fiberglass Loose Fill Insulation	2.40
Inside Air Film (Heat Flow Horizontal)	0.25
Outside Air Film (Heat Flow Horizontal)	0.68
3.5 inch Fiberglass Batt (Wood Frame)	10.00
3.5 inch Fiberglass Batt (Steel Frame)	5.50
3.5 inch Air Space	0.91
Wood Siding	0.81
Metal Siding	0.00
8 inch Heavyweight Concrete	0.48
1 inch Stucco	0.20

A baseline U-Factor (without any insulation added) was calculated for each wall and roof assembly. If the baseline U-Factor was lower than the Standard requirement, it was used. Otherwise, insulation was added to the baseline assembly to meet the Standard U-Factor requirements.

The metal roof assembly required special handling. In metal buildings, it was assumed that batts of fiberglass are laid on the purlins and then a metal roof panel is attached, compressing the fibrous insulation locally at the purlins. Only specific increments of U-Factor were available based the thickness of batts used. The North American Insulation Manufacturers Association (NAIMA) has published a document entitled Guide to Insulating Metal Buildings for Compliance to ASHRAE 90.1-2010[5] (NAIMA, 2013) that details the U-Factors of a variety of these assemblies. This guide was used to identify U-

[5] http://www.naima.org/publications/MB304.PDF

Factors and matched with the Standard 90.1-1989 requirements. It was assumed that fiberglass batts were used exclusively for all roof systems that had U-Factors in excess of 0.046 Btu/(hr ft^2 °F). For U-Factors less than this value, it was assumed that continuous insulation made of polyisocyanurate was added to the underside of the purlins to obtain the required U-factor.

For mass wall systems with interior insulation, the baseline assumed no cavity insulation in the steel framing cavity. The first insulation improvement was to add R-11 fiberglass batts to the cavity yielding a U-Factor of 0.132 Btu/(hr ft^2 °F). For U-Factors lower than this value, it was assumed that continuous insulation made of polyisocyanurate were added to the interior of the stucco layer to obtain the required thermal performance level. For mass wall systems with exterior insulation, it was assumed that continuous insulation made of polyisocyanurate was added to the interior of the stucco layer to obtain the required thermal performance level. For wood and steel framed walls, the first insulation improvement was to add R-11 fiberglass batts to the cavity yielding a U-Factors of 0.082 and 0.130 Btu/(hr ft^2 °F), respectively. To reduce the U-Factor below these levels, it was assumed that continuous insulation made of polyisocyanurate was added to the interior of the siding to obtain the required thermal performance level.

Similar to metal roofs, metal walls needed special handling. Again, the NAIMA report was used to identify wall system U-Factors available with the modification of fiberglass batt insulation. It was assumed that fiberglass batts were used exclusively for all wall systems that had U-Factors in excess of 0.081 Btu/(hr ft^2 °F). For U-Factors less than this value, we assumed that continuous insulation made of polyisocyanurate was added to the underside of the purlins to obtain the required thermal performance level. The thermal properties of all components of new and existing construction are given in Appendix B.

B2. Simulation Results

The prototype EnergyPlus models were modified for various wall and roof insulation levels for all 16 building types in 15 climatic locations. Overall 1,440 models were created based on the modifications. All the 1,920 models (prototype models and modified models) were simulated and the results for further regression analysis were collected in terms of electricity and gas savings for cooling and heating energy consumption.

The simulation results showed that for certain buildings in hot and warm climatic locations adding insulation would not make any significant difference in the cooling energy consumption. In fact it might increase the cooling energy consumption. This kind of results might be confusing to someone not familiar with heat transfer processes. One solution might be to add both heating and cooling energy savings and present the results in terms of overall HVAC energy savings but this might not be an elegant option due to different prices for fuel used for heating and cooling. The presentation of results is further complicated by the fact that some building types use electric resistance heating while others buildings use natural gas for the heating. One option would be to create separate electric and gas heating savings but it would add another set of equations and might not represent the reality as electric bill for heating is generally added in overall electric bill for a particular building. Adding electric and gas heating savings together poses another challenge for the heating savings data presentation. As the main aim of this analysis is to come up with the simplified equations, it was decided to use the commonly use units and types by the industry stakeholders i.e. the savings were presented in terms of electricity and natural gas savings and the units kWh and kBtu, respectively were used for the data presentation.

B3. Regression Analysis

Once the simulation results were collected for all the cases, next step was to determine if a simplified method of estimating the impact of insulation can be obtained based on the simulation results for all the building types. The simplified equations for determining heating and cooling energy savings based on the annual cooling degree days (CDD), heating degree days (HDD), diffuse and direct solar radiation as independent variable were developed for each building type considered in his analysis. Engineering Equation Solver (EES) and Excel were used for the regression analysis. Several combinations of input variables were considered during the simplified equation development process. As the main purpose of development of the regression based equations was to come up with a simplified set of equations that can predict the electricity and gas savings with a small number of input variables. The number of independent (input) variables was also limited by total number of data points available. For any insulation upgrade for each building type only 15 data points, corresponding to 15 climatic locations were available. As expected, CDD and HDD were most influential in electricity and gas savings equations respectively. After analyzing several combinations of independent input variables, it was determined that CDD or HDD, Direct normal solar (DS) and diffuse solar (DIFF) would produce the best set of equations for most for most of the building types. Final set of equations selected were of the form:

$$\text{Savings}=a1*CDD + a2*CDD^2 + a3*DS + a4*DS^2 + a5*DIFF + a6*DIFF^2 +$$

$$a7*CDD*DS + a8*CDD*DIFF + a9*DS*DIFF$$

Where: CDD is cooling degree days (Base 18.3C/65F)and DS is annual daily average direct normal solar radiation (Wh/m^2/day) and DIFF is annual daily average diffuse solar radiation (Wh/m^2/day). As the independent input variables are generally available in SI units s, e.g. all the Typical Meteorological Year (TMY) data, which are available for a large number of locations in the US, are in SI units. The ".stat" file available with TMY data, which can be downloaded from EnergyPlus website[6] , contains all the independent variable needed for using these equations for predicting the electricity and gas savings.

The preliminary analysis showed that for some buildings, the equation predicted and simulated results matched pretty well while for another set of other buildings the results did not match that well. The buildings or cases for which the results did not match different set of independent variables were investigated. For example, using the additional variables the heating energy savings gave much better results. The goal of the final analysis was to come up with the equations which utilized simplified and easily available input data. These equations can then be used for calculating the approximate heating and cooling energy savings due to the insulation upgrade in a typical building without using the detailed whole building energy simulation tools. Since the energy savings calculations presented here are based on the typical buildings with a specific set of building parameters, such as building geometry, floor area, number of stories, window to wall ratio, internal loads, lighting and HVAC systems, it was difficult to generalize

[6] www.energyplus.gov/weather

the results with a generic set of equations which can be used for any building with different parameters in a particular building category. One of the objectives of this study was to develop a simplified set of equations with a limited number of input variables for the ease of use. Therefore, the simulated electricity and gas energy savings for each building type were normalized with respect to building floor area i.e. the electricity and gas savings results were presented in terms of kWh/ft^2 and $kBtu/ft^2$ respectively. Separate sets of equations were developed for electricity and gas savings. Several iterations were made so that the input variables, such as CDD, HDD, WS, DS and Diff, were considered during the analysis to determine the best set which can be used for the majority of building types with high coefficient of determination, R^2. It is to be noted that, as with any simplified approach, this analysis was based on a small data set, i.e. 15 data points representing 15 climatic locations for each type of building. Therefore, the large degree of freedom for input variables did not exist for increasing the accuracy of the equations. For example, just using 4 input variable with cross terms can give a perfect set of equations (R^2=1) for any building type but would not be a representative equation for the data points outside this range. In general, a set of 3 input variables with cross term variables resulted in a good fit for most of the building types. The following sets of regression equations were developed for new and existing construction:

a. Electricity savings - Upgraded wall insulation
b. Gas savings - Upgraded wall insulation
c. Electricity savings - Upgraded roof insulation
d. Gas savings - Upgraded roof insulation
e. Electricity savings - Upgraded wall and roof insulation
f. Gas savings - Upgraded wall and roof insulation

Overall a total of 192 sets of coefficients (a1-a9), 96 each for new and existing construction, were developed for all 16 building types considered in this analysis. For majority of the buildings, input variables of CDD, DS and DIFF for electricity savings, and HDD, DS and DIFF for gas savings were used to derive the equations. The derived equations were of the form:

$$\text{electricity savings} = \text{a1*CDD} + \text{a2*}CDD^2 + \text{a3*DS} + \text{a4*}DS^2 + \text{a5*DIFF} + \text{a6*}DIFF^2 +$$

$$\text{a7*CDD*DS} + \text{a8*CDD*DIFF} + \text{a9*DS*DIFF}$$

For gas savings, a similar equation is used with CDD replaced by HDD.

Table 16 and Table 17 summarize the constants of the equations for new and existing constructions for electricity savings. The results for the rest of the cases are provided in Appendix C.

Table 15 : Summary of coefficient for upgraded roof insulation electricity savings for new construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	-1.48E-02	-1.97E-06	1.24E-02	-6.61E-07	-2.32E-02	1.23E-05	2.30E-06	4.05E-06	-4.75E-06	0.72
Medium Office	-6.11E-03	-7.10E-07	3.14E-03	-8.79E-08	2.62E-03	4.13E-07	7.41E-07	2.37E-06	-2.13E-06	0.87
Large Office	9.88E-04	5.34E-08	-1.49E-05	2.12E-08	1.03E-04	1.01E-07	-8.37E-08	-3.35E-07	-1.02E-07	0.95
Mid-rise Apartment	2.90E-04	-6.96E-07	7.39E-03	-2.45E-07	-1.62E-02	9.18E-06	5.71E-07	-9.16E-07	-3.39E-06	0.87
High-rise Apartment	-2.94E-03	-3.83E-07	2.18E-03	-5.30E-08	-9.33E-04	1.32E-06	3.77E-07	1.11E-06	-1.32E-06	0.80
Quick Service Restaurant	-5.13E-03	-1.03E-06	4.60E-03	-2.53E-07	-9.93E-03	4.68E-06	9.34E-07	1.78E-06	-1.51E-06	0.97
Full Service Restaurant	-9.71E-03	-1.05E-06	3.15E-03	-2.39E-07	-5.84E-03	2.63E-06	1.36E-06	3.32E-06	-8.25E-07	0.99
Hospital	3.07E-03	-8.72E-08	1.71E-03	1.77E-08	-2.97E-03	2.34E-06	-1.21E-07	-1.11E-06	-1.19E-06	0.90
Outpatient Healthcare	-3.14E-02	-3.93E-06	1.74E-02	-6.88E-07	-1.43E-03	7.26E-06	3.92E-06	1.17E-05	-9.86E-06	0.84
Small Hotel	-2.64E-02	-1.71E-06	5.32E-03	-2.08E-07	1.16E-02	-2.61E-06	2.27E-06	1.02E-05	-3.68E-06	0.90
Large Hotel	1.71E-03	-3.99E-07	4.36E-03	-1.03E-07	-9.08E-03	5.43E-06	2.02E-07	-8.97E-07	-2.24E-06	0.92
Primary School	5.72E-03	-1.32E-06	1.32E-02	-3.14E-07	-2.70E-02	1.77E-05	8.44E-07	-3.67E-06	-7.09E-06	0.78
Secondary School	1.99E-03	-8.58E-07	9.33E-03	-2.10E-07	-1.78E-02	1.12E-05	5.42E-07	-1.35E-06	-4.93E-06	0.87
Stand-Alone Retail	1.08E-02	-1.27E-06	1.64E-02	-1.84E-07	-2.93E-02	2.00E-05	1.31E-07	-4.76E-06	-9.55E-06	0.83
Strip Mall	-9.41E-03	-2.68E-06	2.46E-02	-7.66E-07	-4.90E-02	2.87E-05	2.41E-06	1.03E-06	-1.18E-05	0.89
Warehouse	1.24E-02	1.68E-06	-4.05E-03	3.53E-07	1.09E-02	-4.68E-06	-1.56E-06	-4.32E-06	1.00E-06	0.77

Table 16: Summary of coefficient for upgraded roof insulation electricity savings for existing construction

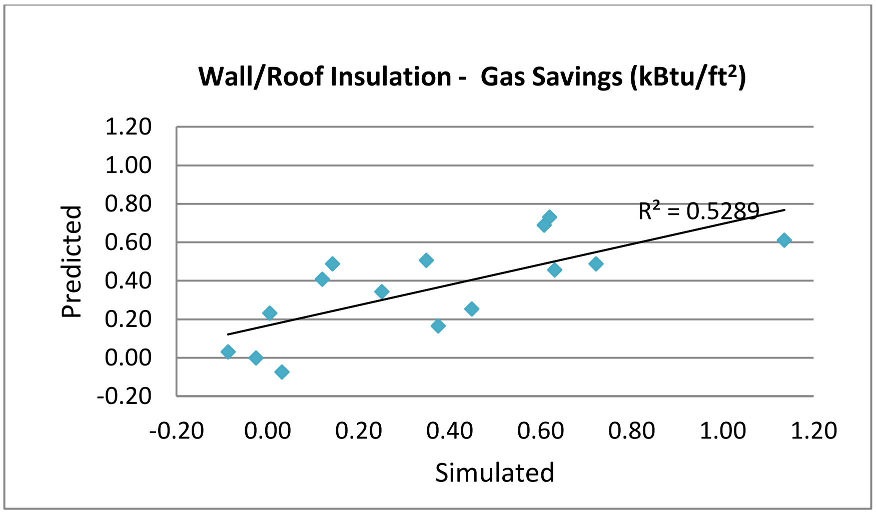
Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	6.41E-04	5.85E-08	1.02E-04	-8.47E-09	-1.01E-04	-2.09E-08	-9.03E-08	-9.63E-08	-9.93E-10	0.87
Medium Office	1.17E-03	9.10E-08	-2.99E-04	2.24E-08	6.97E-04	-2.83E-07	-1.32E-07	-3.90E-07	8.05E-08	0.81
Large Office	1.32E-04	1.02E-08	-7.97E-05	4.88E-09	2.02E-04	-9.63E-08	-1.85E-08	-2.40E-08	2.49E-08	0.99
Mid-rise Apartment	5.84E-04	4.08E-08	-2.36E-04	1.50E-08	5.56E-04	-2.66E-07	-7.42E-08	-1.49E-07	7.79E-08	0.85
Quick Service Restaurant	1.95E-03	2.14E-07	-1.13E-03	6.31E-08	2.49E-03	-1.28E-06	-3.06E-07	-4.13E-07	4.30E-07	0.88
Full Service Restaurant	4.32E-03	4.56E-07	-2.51E-03	1.70E-07	5.88E-03	-2.78E-06	-6.70E-07	-9.52E-07	7.77E-07	0.89
Hospital	8.58E-04	8.85E-08	-6.21E-04	3.13E-08	1.44E-03	-7.26E-07	-1.26E-07	-2.04E-07	2.40E-07	0.88
Outpatient Healthcare	2.33E-03	1.79E-07	-7.50E-04	4.26E-08	1.46E-03	-7.03E-07	-2.60E-07	-7.91E-07	2.93E-07	0.78
Small Hotel	-1.86E-03	-1.94E-07	5.99E-04	-3.73E-08	-7.80E-04	4.58E-07	2.23E-07	6.67E-07	-2.67E-07	0.70
Large Hotel	3.76E-05	4.27E-09	-3.40E-05	2.27E-09	8.71E-05	-4.03E-08	-6.73E-09	-2.79E-09	7.26E-09	0.78
Primary School	2.96E-03	2.87E-07	-1.38E-03	8.21E-08	3.22E-03	-1.59E-06	-3.99E-07	-8.07E-07	4.82E-07	0.86
Secondary School	1.87E-03	1.70E-07	-8.02E-04	4.63E-08	1.87E-03	-9.37E-07	-2.43E-07	-5.05E-07	2.91E-07	0.84
Stand-Alone Retail	8.22E-03	7.25E-07	-1.57E-03	1.22E-07	3.39E-03	-1.57E-06	-9.31E-07	-2.75E-06	4.71E-07	0.88
Strip Mall	3.36E-03	2.94E-07	-7.67E-04	5.20E-08	1.58E-03	-8.21E-07	-4.44E-07	-9.80E-07	2.92E-07	0.92
Super Market	4.30E-03	3.08E-07	-1.09E-03	8.10E-08	2.43E-03	-1.11E-06	-5.00E-07	-1.32E-06	3.39E-07	0.82
Warehouse	3.81E-04	3.58E-08	-1.96E-04	8.08E-09	4.99E-04	-2.66E-07	-4.82E-08	-8.54E-08	8.53E-08	0.90

As seen in Table 16and Table 17, the equations showed a strong fit ($R^2 > 0.95$) for all the building types for new construction and a good correlation ($R^2 > 0.80$) for majority of existing building types. However, for a small set of existing construction buildings, equations for gas savings for upgraded insulation roof and wall insulation did not show a strong fit. A different set of equations was attempted for the cases not showing a strong fit. The new set of equations did improve the fitness in the cases considered. For example, for an existing large office building, the gas savings fit improved to R^2=0.86 from R^2 of 0.53.

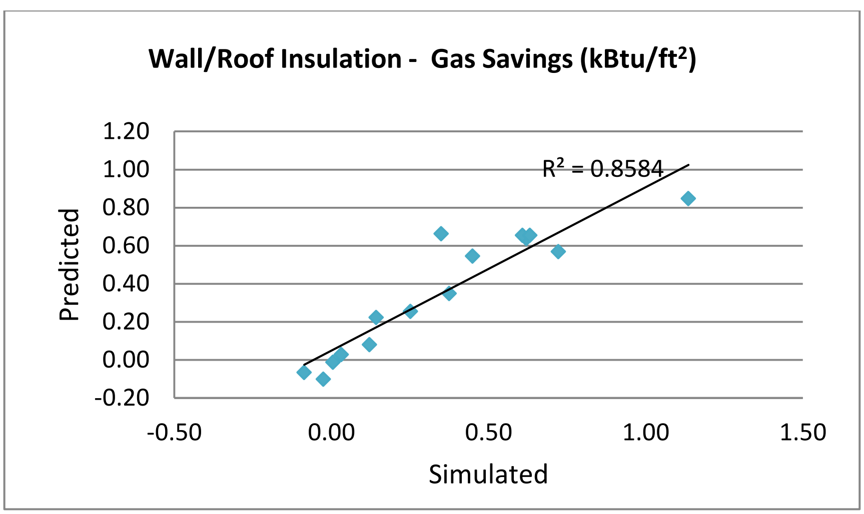
The modified equation for an existing large office building has the following form:

$$\text{Gas Savings} = \text{a0} + \text{a1*DS*DIFF} + \text{a2*HDD*DIFF} + \text{a3*}HDD^2 + \text{a4*}DS^3 +$$
$$\text{a5*DIFF*}HDD^2 + \text{a6*DIFF*}DS^2$$

Figure 3 shows the improvement in the prediction by using the modified equation. In Figure 3 the X-Axis shows the EnergyPlus simulated results and Y-axis show the savings results predicted using the regression equation.



(a)



(b)

Figure 3: Gas savings prediction of upgraded wall and roof insulation of an existing large office building, (a) with generalized equation, (b) with modified equation

In general, electricity and gas savings for the majority of the building types can be expressed by simplified sets of equations. The coefficient of determination (R^2) for the derived equations for upgraded walls and roof insulation cases for new and existing constructions are given in Table 18 and Table 19 respectively.

Table 17: Coefficient of determination (R^2) for the derived equations for new construction

Building Type	Electricity savings-Upgraded wall and roof insulation	Electricity savings-Upgraded roof insulation	Electricity savings-Upgraded wall insulation	Gas savings-Upgraded wall and roof insulation	Gas savings-Upgraded roof insulation	Gas savings-Upgraded wall insulation
Small Office	0.73	0.98	0.72	1.00	1.00	1.00
Medium Office	0.86	0.96	0.87	0.99	0.88	0.99
Large Office	0.99	0.97	0.95	1.00	1.00	1.00
Mid-rise Apartment	0.95	1.00	0.87	1.00	1.00	1.00
High-rise Apartment	0.82	0.98	0.80	1.00	1.00	1.00
Quick Service Restaurant	0.98	0.99	0.97	0.99	0.99	0.99
Full Service Restaurant	0.99	0.99	0.99	0.99	0.94	0.99
Hospital	0.94	0.96	0.90	1.00	1.00	0.99
Outpatient Healthcare	0.85	0.98	0.84	1.00	0.99	0.93
Small Hotel	0.88	0.95	0.90	1.00	1.00	1.00
Large Hotel	0.97	0.98	0.92	0.99	1.00	0.97
Primary School	0.84	0.99	0.78	0.98	0.98	0.98
Secondary School	0.91	0.99	0.87	0.99	0.91	0.99
Stand-Alone Retail	0.87	0.89	0.83	1.00	1.00	1.00
Strip Mall	0.91	0.99	0.89	1.00	1.00	1.00
Warehouse	0.82	0.98	0.77	0.99	1.00	0.99

Color codes	>0.9	0.8-0.9	0.6-0.8	<0.6

Table 18: Coefficient of determination (R^2) for the derived equations for existing constructions

Building Type	Electricity savings-Upgraded wall and roof insulation	Electricity savings-Upgraded roof insulation	Electricity savings-Upgraded wall insulation	Gas savings-Upgraded wall and roof insulation	Gas savings-Upgraded roof insulation	Gas savings-Upgraded wall insulation
Small Office	0.87	0.97	0.95	0.96	0.49	0.78
Medium Office	0.81	0.98	0.95	0.81	0.99	0.94
Large Office	0.99	0.94	0.95	0.88	0.56	0.53
Mid-rise Apartment	0.85	0.98	0.98	0.79	0.66	0.82
Quick Service Restaurant	0.88	0.98	0.96	0.94	0.60	0.90
Full Service Restaurant	0.89	0.98	0.97	0.95	0.62	0.95
Hospital	0.88	0.95	0.95	0.73	0.69	0.68
Outpatient Healthcare	0.78	0.98	0.96	0.92	0.95	0.95
Small Hotel	0.70	0.96	0.92	0.96	0.75	0.90
Large Hotel	0.78	0.98	0.94	0.71	0.30	0.58
Primary School	0.86	0.98	0.95	0.68	0.72	0.69
Secondary School	0.84	0.98	0.97	0.80	0.60	0.80
Stand-Alone Retail	0.88	0.89	0.83	0.87	0.50	0.72
Strip Mall	0.92	0.99	0.96	0.85	0.79	0.89
Super Market	0.82	0.94	0.90	0.88	0.48	0.75
Warehouse	0.90	0.99	0.98	0.91	0.79	0.90
Color codes	>0.9	0.8-0.9	0.6-0.8	<0.6		

As seen in Table 18 and Table 19, for some building types the correlation was quite poor. The reason for poor correlation was the fact that for some cases the insulation values for new construction were lower than the values for the existing constructions. The negative energy savings for those cases, especially in the cold climates, skewed the equations and thus shows poor correlation. In other cases, the savings were very small in some heating dominated locations. The inconsistency in the case of existing building was mainly due to the non-uniformity in the insulation level differences between the base case (1989 complaint insulation levels) and the target case (90.1-2013 compliant insulation levels). In case of new construction, the difference in insulation levels between the base case (no insulation) and target case (

90.1-2013 compliant insulation levels) was consistent which was reflected in very good correlation (R^2 > 0.80) between the simulation and equation predicted savings results.

To check the validity of the developed equations, two building types, medium office and standalone retail, were simulated for Oak Ridge, TN (climate zone 4 A) and the results were compared with the regression equations based electricity and gas consumption using HDD,CDD, DS and DIFF values for Oak Ridge. Table 20 shows the EnergyPlus simulated and regression equation predicted electricity and gas savings results of a medium office and a standalone retail building.

Table 19: EnergyPlus simulated and regression equation predicted electricity and gas savings for a medium office and a standalone retail building in Oak Ridge, TN

Case Description	Electricity savings (kWh/ft^2)		Gas savings ($kBtu/ft^2$)	
	EnergyPlus Simulated	Equation predicted	EnergyPlus Simulated	Equation predicted
Medium Office				
Existing construction				
Baseline case - ASHRAE 90.1-1989 code compliant				
Upgraded wall insulation (ASHRAE 90.1-2013 compliant wall)	0.27	0.07	0.03	0.02
Upgraded roof insulation (ASHRAE 90.1-2013 compliant roof)	0.06	0.07	0.05	0.05
Upgraded wall and roof insulation (ASHRAE 90.1-2013 compliant wall and roof)	0.33	0.13	0.09	0.07
New construction				
Baseline case - No wall and roof insulation				
Upgraded wall insulation (ASHRAE 90.1-2013 compliant wall)	2.12	2.20	1.11	1.57
Upgraded roof insulation (ASHRAE 90.1-2013 compliant roof)	1.13	1.22	1.06	0.65
Upgraded wall and roof insulation (ASHRAE 90.1-2013 compliant wall and roof)	3.29	3.39	2.52	2.24
Standalone Retail				
Existing construction				
Baseline case - ASHRAE 90.1-1989 code compliant				
Upgraded wall insulation (ASHRAE 90.1-2013 compliant wall)	-0.07	0.06	0.54	0.35
Upgraded roof insulation (ASHRAE 90.1-2013 compliant roof)	-0.09	0.05	1.52	1.61
Upgraded wall and roof insulation (ASHRAE 90.1-2013 compliant wall and roof)	-0.10	0.12	2.06	1.96
New construction				
Baseline case - No wall and roof insulation				
Upgraded wall insulation (ASHRAE 90.1-2013 compliant wall)	8.03	9.06	24.95	24.80
Upgraded roof insulation (ASHRAE 90.1-2013 compliant roof)	0.36	0.16	6.22	6.39
Upgraded wall and roof insulation (ASHRAE 90.1-2013 compliant wall and roof)	8.46	9.42	31.48	31.61

For most cases, the regression equation predicted electricity and gas savings results for both the building types and insulation upgrade cases agree with the EnergyPlus simulated results. As mentioned earlier, for some locations the electricity and/or savings results did not follow the increasing or decreasing CDD or HDD trends. Based on the regression equations developed above, a simple Excel based tool was developed which could be used to estimate the electricity and gas savings due to insulation upgrades by providing only a few parameters i.e. the building type, floor area, heating degree days, cooling degrees days, direct normal and diffuse solar radiation.

B4. Indirect environmental Impact Calculations

This section demonstrates the use of simplified tool and the methodology developed by Shrestha et al., 2014 to calculate the indirect environmental impact. Here, indirect environmental impact factors of insulation materials were calculated using the prototype building models of three building types in two climate zones, listed in Table 21. 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 were followed for existing and new construction, respectively.

Table 20. Building and construction details

<table>
<tr><th rowspan="3">Building type</th><th colspan="2" rowspan="2">Construction</th><th colspan="2" rowspan="2">Exterior envelope area (m2)</th><th rowspan="3">Climate zone (City)</th><th colspan="4">Insulation R-value (m2-K/W)</th></tr>
<tr><th colspan="2">New construction</th><th colspan="2">Existing construction</th></tr>
<tr><th>Wall</th><th>Roof</th><th>Wall</th><th>Roof</th><th>Wall</th><th>Roof</th><th>Wall</th><th>Roof</th></tr>
<tr><td rowspan="2">Highrise apartment</td><td rowspan="2">Steel framed</td><td rowspan="2">Insulation entirely above deck (IEAD)</td><td rowspan="2">3,855</td><td rowspan="2">784</td><td>2A (Houston)</td><td>1.71</td><td>4.31</td><td>NA</td><td>NA</td></tr>
<tr><td>5A (Chicago)</td><td>2.82</td><td>5.30</td><td>NA</td><td>NA</td></tr>
<tr><td rowspan="2">Medium office</td><td rowspan="2">Steel framed</td><td rowspan="2">IEAD</td><td rowspan="2">1,978</td><td rowspan="2">1,661</td><td>2A (Houston)</td><td>1.71</td><td>4.31</td><td>0.74</td><td>2.40</td></tr>
<tr><td>5A (Chicago)</td><td>2.82</td><td>5.30</td><td>1.73</td><td>3.11</td></tr>
<tr><td rowspan="2">Standalone retail</td><td rowspan="2">Mass</td><td rowspan="2">IEAD</td><td rowspan="2">1,177</td><td rowspan="2">2,294</td><td>2A (Houston)</td><td>0.85</td><td>4.31</td><td>0.09</td><td>2.40</td></tr>
<tr><td>5A (Chicago)</td><td>1.64</td><td>5.30</td><td>1.34</td><td>3.11</td></tr>
</table>

The building types and climate zones were chosen based on their relative fractions of the total volume of new commercial construction in the U.S., to represent 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 construction from 2003 to 2007

(Jarnagin and Bandyopadhyaya, 2010). Further, the three building types chosen represent different occupancy and usage profiles; for example, the medium office can be expected to have higher occupancy and energy usage during the daytime and the opposite can be expected for highrise apartments. Climate zone 2A, defined by ASHRAE 90.1, is cooling (hot or warm weather) dominated and contains 15.2% of new construction; climate zone 5A is heating (cold weather) dominated with 19.4% of new construction (Jarnagin and Bandyopadhyaya, 2010).

The energy savings due to insulation materials, referred to as avoided operational energy (AOE), were calculated as

$$AOE = OEpe – OEcl \qquad (4)$$

Where

OEpe = operational energy with pre-existing insulation

OEcl = 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 construction, OEpe is defined for the two scenarios as:

New construction: OEpe is the energy consumed with an uninsulated building envelope.

Existing construction: OEpe 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.

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 using the insulation materials of interest to provide code-level insulation required by the current version of ASHRAE Standard 90.1 (latest version is 2013).

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

$$AOE_{Elec} = OEpe,Elec – OEcl,Elec \qquad (5)$$

$$AOE_{NG} = OEpe,NG – OEcl,NG \qquad (6)$$

OEpe and OEcl 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 (3) and (4) 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.

New Construction

Table 22 lists the site-energy consumption results from the EnergyPlus simulations of the new construction cases. The baseline case is the one without any wall or roof insulation ('No Insulation') and the other cases represent the upgraded building models with wall and roof insulation according to the 2013 version of ASHRAE 90.1. The energy consumption was calculated separately based on fuel type – natural gas and electricity. The energy savings due to upgraded wall or roof (or both) insulation is simply the difference between the baseline case and the respective upgraded case.

Table 21. EnergyPlus predicted annual site-energy consumption for the new construction cases

Location	Natural gas (MJ)				Electricity (MJ)			
	No Insulation	Wall Insulation	Roof Insulation	Wall & Roof Insulation	No Insulation	Wall Insulation	Roof Insulation	Wall & Roof Insulation
	Highrise apartment							
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
	Medium office							
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
	Standalone retail							
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 (Deru and Torcellini, 2007; EnergyStar, 2014):

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.

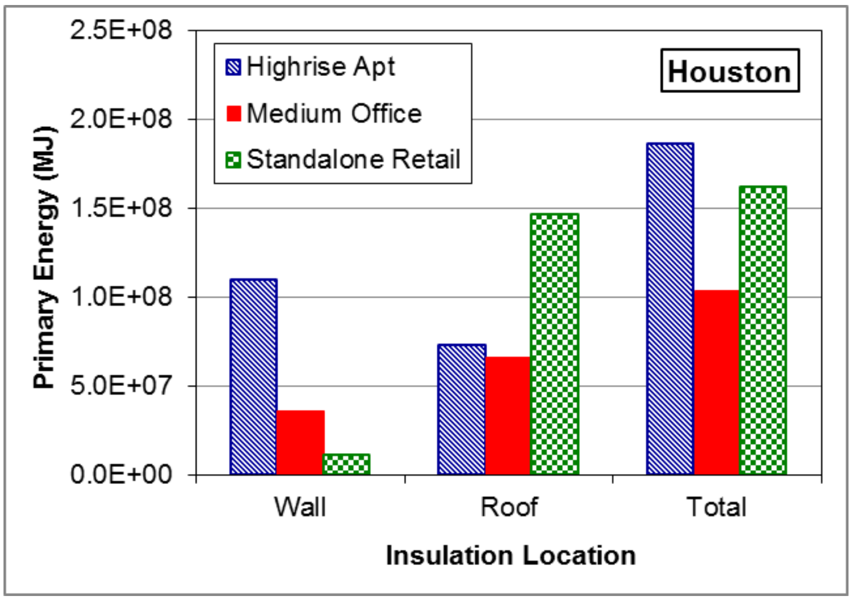
The CO2 emissions were estimated based on the following primary energy-to-emission conversion factors (EPA, 2014):

Natural gas: 53.06 kg CO_2 per MMBtu (0.0503 kg CO_2/MJ)

Electricity: 1,218.17 lb CO_2 per MWh (0.1535 kg CO_2/MJ) (Houston); 1,503.47 lb CO_2 per MWh (0.1894 kg

CO_2/MJ) (Chicago)

The resulting total primary energy savings and avoided CO_2 emissions for the different new construction scenarios (building type and climate zone) are shown in Figure 4 and Figure 5. 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 mentioned earlier, the energy savings and avoided emissions are positive.



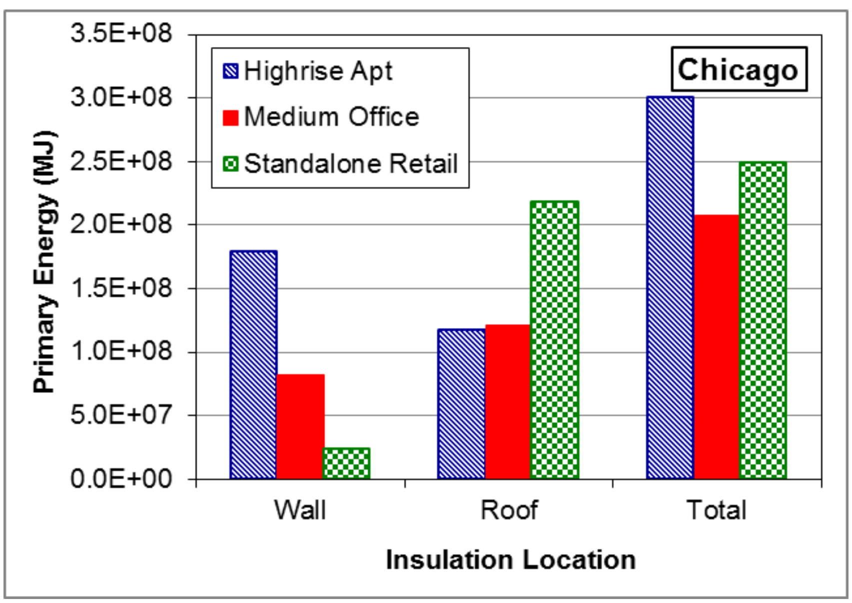


Figure 4. Indirect environmental impacts – primary energy savings over 60 years for new construction cases.

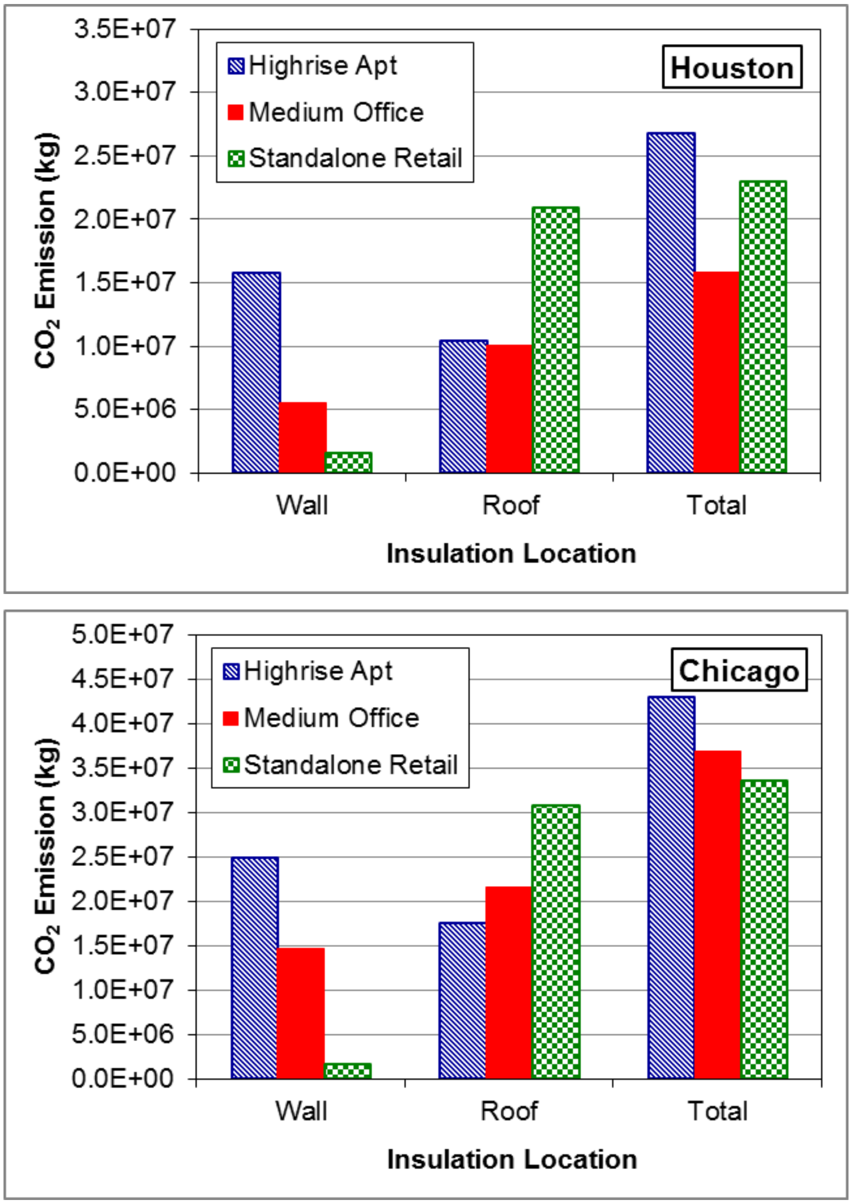


Figure 5. Indirect environmental impacts – avoided CO_2 emissions over 60 years for new construction cases.

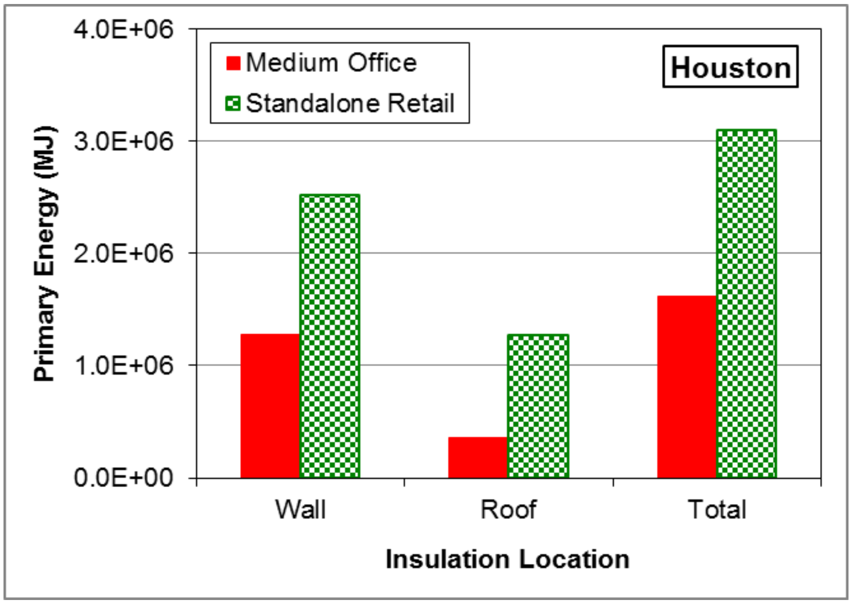
Existing Construction

Table 23 lists the modeled site-energy consumption results for the existing construction cases. The baseline case is the one with walls and roof insulated according to the 1989 version of ASHRAE 90.1 ('1989 Baseline') and the other cases represent the upgraded building models with wall and/or roof insulation according to the 2013 version of ASHRAE 90.1. Again, the energy savings due to upgraded wall or roof (or both) insulation is simply the difference between the baseline case and the respective upgraded case. The existing construction cases assumed that the building received only an envelope insulation upgrade and all other buildings characteristics and equipment, lighting and HVAC systems were not changed/upgraded. Again, the 'highrise apartment' case is not applicable to existing construction.

Table 22. EnergyPlus predicted annual site-energy consumption for the existing construction cases

Location	Natural gas (MJ)				Electricity (MJ)			
	1989 Baseline	Wall - 2013	Roof - 2013	Wall & Roof - 2013	1989 Baseline	Wall - 2013	Roof - 2013	Wall & Roof - 2013
	Medium office							
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
	Standalone retail							
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

Using the aforementioned conversion factors, the resulting total primary energy savings and avoided CO_2 emissions for the different existing construction scenarios (building type and climate zone) are shown in Figure 6 and Figure 7. For the existing construction cases, the additional service life for the buildings after upgrading the roof or wall insulation was assumed to be 30 years (assuming a building life of 60 years and the insulation upgrades taking place at 30 years). Therefore, the primary energy savings and avoided CO_2 emissions for the existing construction cases are over 30 years.



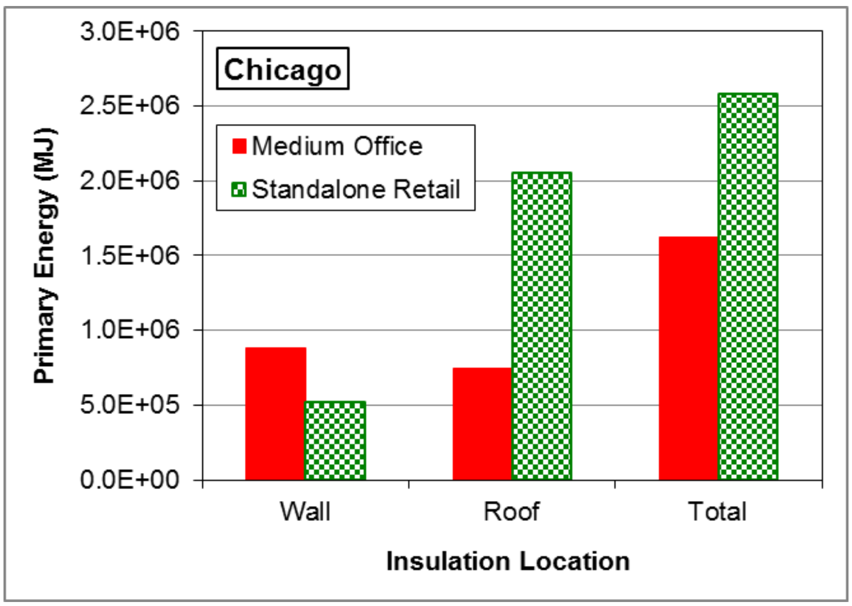


Figure 6. Indirect environmental impacts – primary energy savings over 30 years for existing construction cases.

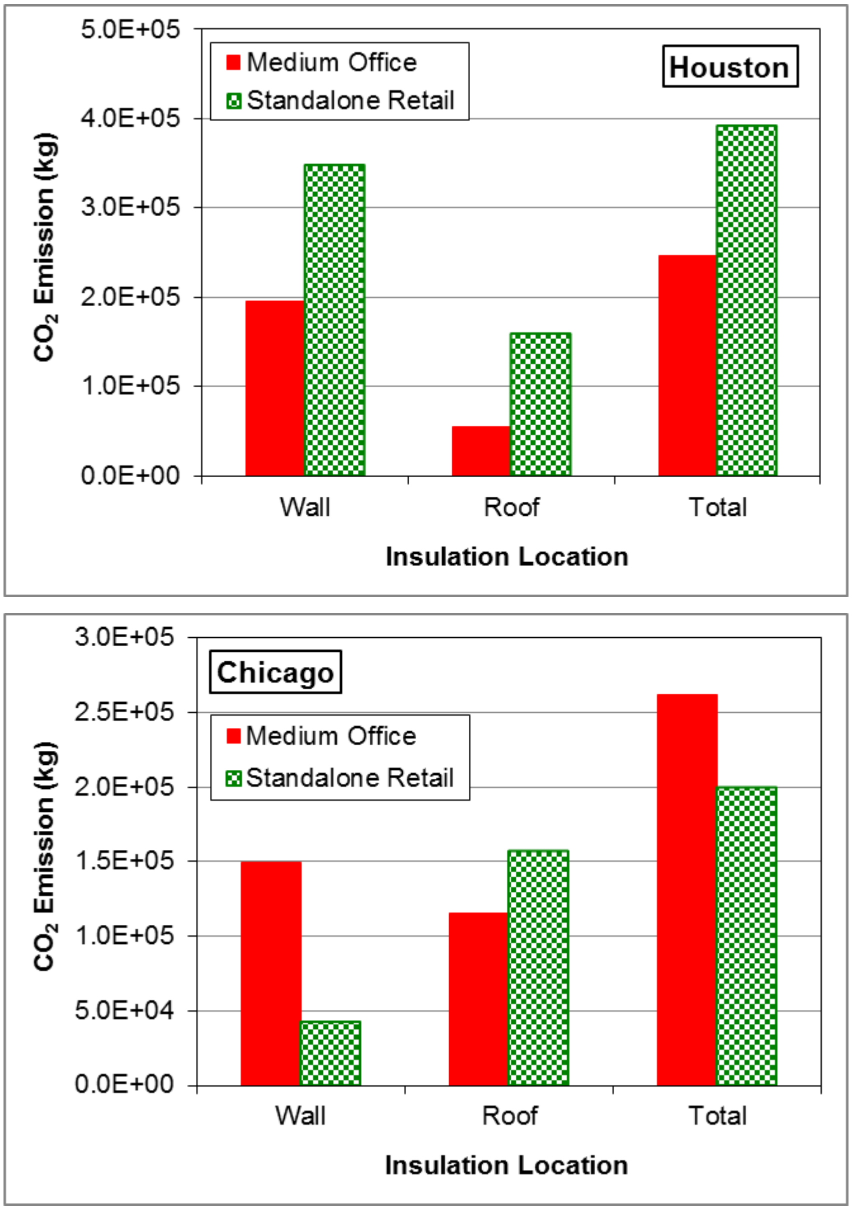


Figure 7. Indirect environmental impacts – avoided CO_2 emissions over 30 years for existing construction cases.

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 24 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 levels were upgraded to 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 23. Indirect environmental impact factors on a per functional unit basis

Building type	Climate zone (City)	New construction		Existing construction	
		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

C. Net Lifetime Environmental Impact assessment

Table 25 and Table 26 present the summaries of the two impact categories (primary energy and GWP) at the different life cycle stages for polyiso insulation in a highrise apartment in the two climate zones. The data presented are for new construction cases where both the roof and wall insulation were added, and take into account an assumed insulation loss rate of 5% and the roof insulation replacement. It is evident that the indirect impacts dominate the overall lifetime impacts of the polyiso insulation materials for the scenarios considered.

Table 24. Lifetime impacts of polyisocyanurate foam insulation in a highrise apartment in climate zone 2A

Product: Polyisocyanurate foam (with pentane)		**Functional unit (FU) (kg): 0.68**	
Building: Highrise apartment	**Location: Houston (2A)**	**Life cycle impact category**	
Life cycle stage	**Subcategory**	**Primary energy (MJ/FU)**	**GWP_{100} (kg CO_2e/FU)**
Raw material acquisition		-84.76	-3.46
Manufacturing		-0.42	-0.05
Installation and use	Installation	--	-0.28
	Impacts avoided during use	18645	2685
Disposal		-0.07	-0.17
Transportation		-1.91	-0.05
Net Lifetime Impact		**18558**	**2681**

Table 25. Lifetime impacts of polyisocyanurate foam insulation in a highrise apartment in climate zone 5A

Product: Polyisocyanurate foam (with pentane)		**Functional unit (FU) (kg): 0.68**	
Building: Highrise apartment	**Location: Chicago (5A)**	**Life cycle impact category**	
Life cycle stage	**Subcategory**	**Primary energy (MJ/FU)**	**GWP_{100} (kg CO_2e/FU)**
Raw material acquisition		-80.80	-3.30
Manufacturing		-0.40	-0.05
Installation and use	Installation	--	-0.27
	Impacts avoided during use	19993	2862
Disposal		-0.07	-0.16
Transportation		-1.82	-0.05
Net Lifetime Impact		**19910**	**2858**

Table 27 and Table 28 summarize the net lifetime impacts of all selected insulation materials for new and existing construction cases, respectively, for all building types and climate zones. Again, the data represent cases where both wall and roof insulation levels were upgraded. The main focus of this manuscript was the demonstration of the assessment protocol and calculation methodology, and not comparison of the selected insulation materials. However, some useful insights can be gained by reviewing the results. Overall, the environmental impacts of aerogel, which can be considered a next-generation insulation material, were very similar to those of foam insulation materials; within 0.35% for new construction and 10% for existing construction. Further, extruded polystyrene (XPS) had the lowest GWP impact factor, which, based on sign convention, indicates a greater 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 27 and Table 28 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.

Table 26. Net lifetime environmental impact factors of the selected insulation materials in new construction

Location	Building Type	Product	Net Lifetime Impact Factors		Indirect/Direct Impact Factors	
			Primary energy (MJ/FU)	GWP_{100} (kg CO_2e/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

Table 27. Net lifetime environmental impact factors of the selected insulation materials in existing construction.

Location	Building Type	Product	Net Lifetime Impact Factors		Indirect/Direct Impact Factors	
			Primary energy (MJ/FU)	GWP_{100} (kg CO_2e/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

Finally, in Table 27 and Table 28, the ratios of indirect to direct impact factors (Indirect/Direct Impact Factors) are also listed. For the new construction cases, where insulation upgrade meant increase from no insulation to 2013 code-level insulation, the energy savings and avoided emissions were dominant. For new construction, 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 construction cases, with assumed insulation upgrades from 1989 to 2013 code-levels and remaining building lifetime of 30 years, the indirect impacts were not as high. However, even for existing construction, the indirect impact factors were calculated to be about 5-10 times of the direct impact factors.

Overall, for both new and existing construction, the indirect impacts were predominant, regardless of the insulation material. However, the 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 operational energy savings due to insulation alone and, hence, the indirect impact factors of insulation materials. Further, the results of the assessment for existing construction highlight the issue of diminishing returns with increasing the amount of insulation in walls and roofs beyond a certain level. 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.

VII. Conclusions

The objective of this project was to perform an assessment of the lifetime energy and environmental impacts of building insulation materials based on a previously developed protocol. The developed protocol was used for calculating the lifetime environmental impacts of selected insulation materials. Two Excel-based tools were developed: 1) to calculate embodied energy and GWP (equivalent CO2 emissions) of insulation materials, and 2) to estimate energy savings and avoided environmental impacts due to the use of insulation materials in buildings. The direct environmental impacts were estimated using data from existing literature and life cycle analysis software; the indirect impacts were based on simulations of prototype whole-building models.

This report presents the demonstration of a previously published protocol for estimating the lifetime environmental impacts of insulation materials. The environmental impact factors, direct and indirect, were estimated for the following life cycle stages of the insulation materials: raw material acquisition, manufacturing, installation and use, disposal, and transportation. The environmental impact factors were calculated for two categories: primary energy consumption and global warming potential in terms of equivalent carbon dioxide emissions. The direct environmental impact factors were calculated based on data from existing literature and life cycle assessment (LCA) software.

To calculate the indirect impact of the insulation materials a simple regression based spreadsheet was developed. The regression tool was based on the simulation study carried out to estimate the energy savings potential of insulation upgrades of 16 different commercial buildings in 15 climatic locations in the United States (US). These buildings represent the majority of commercial buildings types in the US and the nationwide impact will be estimated by using the weighting factors for construction volume of various building types at different locations.

Based on the simulation results, the preliminary equations for determining heating and cooling energy savings based on the annual cooling degree days (CDD), heating degree days (HDD), wind speed and solar radiation as independent variable were developed for each building type considered in his analysis. After analyzing several combinations of independent input variables, it was determined that CDD or HDD, direct normal solar (DS) and diffuse solar (DIFF) irradiance produced the best set of equations for most building types. The objective was to develop a simple Excel based tool that can be used to estimate the electricity and gas savings due to insulation upgrades by providing only a few parameters i.e. the building type, floor area, heating degree days, cooling degrees days, direct normal and diffuse solar radiation.

Overall, the indirect impacts dominated the net lifetime impacts for the insulation materials and scenarios considered and the need for standardized calculation or determination methods is emphasized. For the new construction cases, the calculated indirect impact factors were on average about 110 (primary energy) and 285 (GWP100) times the direct impact factors. For existing construction, the indirect impact factors were 5-10 times greater that the direct impact factors. However, if other energy-efficiency measures, in addition to the insulation upgrade, are considered, the direct impacts could become a more significant fraction of the net lifetime impacts and influence the decision-making. There may be a limit beyond which adding further insulation increases the direct impacts but has no further energy savings, as indicated by the assessment of the existing construction cases. This article also highlights the lack of data for certain insulation materials and life cycle stages, a potential area for additional future work.

IX. Anticipated market impact

The market for insulation products in the United States is large, with insulation worth $7.8 Billion being sold annually even in a depressed economy; in times where new construction is heavier; the market can be up to $14 billion. Increasing roof board insulation from R4 to R5 per inch can reduce energy use by 20%. However, these additional savings can have an adverse impact on a building's overall life-cycle greenhouse gas (GHG) emissions depending on the choice of insulation: more efficient insulation may contain up to 200 times more CO2-e (CO2-equivalent) embodied in the insulation, whereas alternatives may provide the same efficiency benefits without adversely impacting environmental performance. This project will help quantify these benefits and allow stakeholders and the building community to make more informed choices. If even 10% of buildings utilized advanced insulation that is both 10% more energy efficient that would correspond to savings of 0.05 Quads, assuming 20% of energy use is for opaque walls and roofs.

XI. Limitations and Future work

The project highlights the lack of data for certain insulation materials and life cycle stages, a potential area for additional future work. It is reiterated that the present calculations are not limited by current commercial applications of insulation materials and do not consider the suitability, or lack thereof, of insulation materials for a given building type. It is not the intention here to provide explicit recommendations purely based on the current environmental impact results. While selecting insulation materials for particular applications, 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. A comprehensive simplified tool to asses both the direct and indirect impact of insulation materials would add value to the LCA users.

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XIII. Appendices

A. Nomenclature, Subscripts and abbreviations

Nomenclature A	Area (m2 or ft2)
FU	Functional unit (kg or lb)
N	Number of functional units
R	Thermal resistance (m2·K/W or h·ft2 ·ºF/Btu)
U	Overall heat transfer coefficient (W/m2·K or Btu/h·ft2 ·ºF)
X	Impact factor (MJ/FU or kg CO2e/FU)
λ	Thermal conductivity (W/m·K or Btu·in/h·ft2.ºF)
ρ	Density (kg/m3 or lb/ft3)

Subscripts:

cl	code-level
Eff	Effective
Elec	Electricity
Env	Envelope
IP	Inch-pound
Mod	Modified
NG	Natural gas
pe	pre-existing
SI	Le Système International d'Unités (International System of Units)

Abbreviations:

ASHRAE	American Society of Heating, Refrigeration, and Air-conditioning Engineers
AOE	Avoided operational energy
DOE	Department of Energy
EI	Ecoinvent
EIA	Energy Information Administration
EPD	Environmental product declaration
EPS	Expanded polystyrene
GHG	Green house gases
GWP	Global warming potential
HVAC	Heating, ventilation, and air-conditioning
IEAD	Insulation entirely above deck
IECC	International Energy Conservation Code
LCA	Life cycle assessment
LCI	Life cycle inventory
OE	Operational energy
SPFA	Spray Polyurethane Foam Alliance
U.S.	United States
XPS	Extruded polystyrene
ORNL	Oak Ridge National Laboratory

B. Wall and roof construction properties

Table B1: Wall construction

Wall Type	Construction Layers	Thickness (m)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)
Mass Wall	Stucco	0.025	0.692	1,858	837
	Concrete HW	0.203	1.311	2,240	837
	Mass NonRes Wall Insulation	0.051	0.049	265	837
	Gypsum	0.013	0.16	785	830
Steel Frame	Wood Siding	0.010	0.11	545	1,210
	Steel Frame NonRes Wall Insulation	0.176	0.049	265	837
	Gypsum	0.013	0.160	785	830
Metal Building	Metal Siding	0.0015	44.96	7,689	410
	Metal Building Semi-Cond Wall Insulation	0.171	0.049	265	837
	Gypsum	0.013	0.16	785	830
Wood Frame	Wood Siding	0.010	0.11	545	1,210
	Wood Frame NonRes Wall Insulation	0.176	0.049	265	837
	Gypsum	0.013	0.16	785	830

Table B2: Roof construction

Roof Type	Construction Layers	Thickness	Conductivity	Density	Specific Heat
		(m)	(W/mK)	(kg/m^3)	(J/kgK)
IEAD	Roof Membrane	0.010	0.160	1,121	1,460
	IEAD NonRes Roof Insulation	0.136	0.049	265	837
	Metal Decking	0.002	45.006	7680	418
Attic and Other	Gypsum	0.013	0.160	785	830
	AtticFloor NonRes Insulation	0.261	0.049	265	837
	Gypsum	0.013	0.160	785	830
Metal Building	Metal Roofing	0.002	45.006	7,680	418
	Metal Semi-Cond Roof Insulation	0.272	0.049	265	837

C. Summary of coefficient for electricity and gas savings

New Construction

Table C1: Summary of coefficient for wall insulation electricity savings for new construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	-2.18E-02	-2.65E-06	1.66E-02	-8.96E-07	-2.93E-02	1.57E-05	3.24E-06	6.15E-06	-6.44E-06	0.73
Medium Office	-1.74E-02	-1.47E-06	4.48E-03	-1.74E-07	1.07E-02	-2.41E-06	1.75E-06	7.00E-06	-3.28E-06	0.86
Large Office	1.81E-03	7.46E-08	-4.27E-04	3.67E-08	1.14E-03	-4.27E-07	-1.35E-07	-5.81E-07	5.61E-08	0.99
Mid-rise Apartment	8.41E-04	-9.02E-07	8.98E-03	-3.47E-07	-1.84E-02	1.03E-05	7.84E-07	-1.25E-06	-3.88E-06	0.95
High-rise Apartment	-9.61E-03	-9.54E-07	3.32E-03	-1.33E-07	4.00E-03	-3.90E-07	1.11E-06	3.83E-06	-2.07E-06	0.82
Quick Service Restaurant	-6.81E-03	-1.28E-06	6.13E-03	-3.38E-07	-1.24E-02	6.04E-06	1.27E-06	2.32E-06	-2.12E-06	0.98
Full Service Restaurant	-1.07E-02	-1.25E-06	3.57E-03	-3.01E-07	-6.25E-03	2.54E-06	1.59E-06	3.75E-06	-7.76E-07	0.99
Hospital	3.91E-03	-7.45E-08	1.45E-03	2.65E-08	-2.36E-03	2.03E-06	-1.63E-07	-1.40E-06	-1.08E-06	0.94
Outpatient Healthcare	-4.39E-02	-5.00E-06	2.02E-02	-8.18E-07	6.44E-03	5.06E-06	5.16E-06	1.68E-05	-1.18E-05	0.85
Small Hotel	-4.64E-02	-3.12E-06	9.44E-03	-4.02E-07	1.76E-02	-3.65E-06	4.14E-06	1.79E-05	-6.38E-06	0.88
Large Hotel	4.05E-03	-3.51E-07	3.93E-03	-8.82E-08	-7.82E-03	4.81E-06	9.78E-08	-1.73E-06	-2.10E-06	0.97
Primary School	5.90E-03	-1.25E-06	1.28E-02	-2.76E-07	-2.61E-02	1.72E-05	7.86E-07	-3.62E-06	-6.93E-06	0.84
Secondary School	2.53E-03	-8.55E-07	9.58E-03	-2.11E-07	-1.83E-02	1.15E-05	5.40E-07	-1.55E-06	-5.08E-06	0.91
Stand-Alone Retail	1.16E-02	-1.57E-06	1.70E-02	-2.31E-07	-2.86E-02	1.98E-05	2.71E-07	-4.86E-06	-9.91E-06	0.87
Strip Mall	-1.33E-02	-2.90E-06	2.50E-02	-7.90E-07	-4.62E-02	2.77E-05	2.75E-06	2.78E-06	-1.21E-05	0.91
Warehouse	1.43E-02	1.85E-06	-4.49E-03	4.07E-07	1.28E-02	-5.40E-06	-1.75E-06	-4.86E-06	9.78E-07	0.82

Table C2: Summary of coefficient for upgraded wall and roof insulation electricity savings for new construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	-1.48E-02	-1.97E-06	1.24E-02	-6.61E-07	-2.32E-02	1.23E-05	2.30E-06	4.05E-06	-4.75E-06	0.72
Medium Office	-6.11E-03	-7.10E-07	3.14E-03	-8.79E-08	2.62E-03	4.13E-07	7.41E-07	2.37E-06	-2.13E-06	0.87
Large Office	9.88E-04	5.34E-08	-1.49E-05	2.12E-08	1.03E-04	1.01E-07	-8.37E-08	-3.35E-07	-1.02E-07	0.95
Mid-rise Apartment	2.90E-04	-6.96E-07	7.39E-03	-2.45E-07	-1.62E-02	9.18E-06	5.71E-07	-9.16E-07	-3.39E-06	0.87
High-rise Apartment	-2.94E-03	-3.83E-07	2.18E-03	-5.30E-08	-9.33E-04	1.32E-06	3.77E-07	1.11E-06	-1.32E-06	0.80
Quick Service Restaurant	-5.13E-03	-1.03E-06	4.60E-03	-2.53E-07	-9.93E-03	4.68E-06	9.34E-07	1.78E-06	-1.51E-06	0.97
Full Service Restaurant	-9.71E-03	-1.05E-06	3.15E-03	-2.39E-07	-5.84E-03	2.63E-06	1.36E-06	3.32E-06	-8.25E-07	0.99
Hospital	3.07E-03	-8.72E-08	1.71E-03	1.77E-08	-2.97E-03	2.34E-06	-1.21E-07	-1.11E-06	-1.19E-06	0.90
Outpatient Healthcare	-3.14E-02	-3.93E-06	1.74E-02	-6.88E-07	-1.43E-03	7.26E-06	3.92E-06	1.17E-05	-9.86E-06	0.84
Small Hotel	-2.64E-02	-1.71E-06	5.32E-03	-2.08E-07	1.16E-02	-2.61E-06	2.27E-06	1.02E-05	-3.68E-06	0.90
Large Hotel	1.71E-03	-3.99E-07	4.36E-03	-1.03E-07	-9.08E-03	5.43E-06	2.02E-07	-8.97E-07	-2.24E-06	0.92
Primary School	5.72E-03	-1.32E-06	1.32E-02	-3.14E-07	-2.70E-02	1.77E-05	8.44E-07	-3.67E-06	-7.09E-06	0.78
Secondary School	1.99E-03	-8.58E-07	9.33E-03	-2.10E-07	-1.78E-02	1.12E-05	5.42E-07	-1.35E-06	-4.93E-06	0.87
Stand-Alone Retail	1.08E-02	-1.27E-06	1.64E-02	-1.84E-07	-2.93E-02	2.00E-05	1.31E-07	-4.76E-06	-9.55E-06	0.83
Strip Mall	-9.41E-03	-2.68E-06	2.46E-02	-7.66E-07	-4.90E-02	2.87E-05	2.41E-06	1.03E-06	-1.18E-05	0.89
Warehouse	1.24E-02	1.68E-06	-4.05E-03	3.53E-07	1.09E-02	-4.68E-06	-1.56E-06	-4.32E-06	1.00E-06	0.77

Table C3: Summary of coefficient for upgraded wall insulation gas savings for new construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	2.74E-04	4.79E-07	-8.09E-03	4.06E-07	1.58E-02	-6.58E-06	2.26E-08	-8.12E-07	2.66E-06	1.00
Medium Office	4.55E-03	-2.46E-07	4.70E-03	-2.00E-07	-1.87E-02	7.20E-06	-4.95E-07	-3.12E-07	-1.08E-06	0.88
Large Office	6.47E-05	1.19E-07	3.95E-03	-1.78E-07	-8.48E-03	3.59E-06	-1.31E-07	7.00E-07	-1.34E-06	1.00
Mid-rise Apartment	-2.48E-03	4.57E-07	1.56E-03	-6.46E-09	-1.58E-04	9.48E-07	1.20E-07	2.49E-06	-1.21E-06	1.00
High-rise Apartment	-7.86E-04	1.81E-07	3.34E-03	-1.85E-07	-8.34E-03	3.19E-06	-9.16E-08	2.18E-06	-8.89E-07	1.00
Quick Service Restaurant	4.82E-03	5.96E-07	-1.79E-02	1.48E-06	1.65E-02	-2.19E-06	2.71E-07	4.16E-07	2.49E-06	0.99
Full Service Restaurant	-7.78E-04	6.76E-07	-2.84E-02	1.99E-06	6.29E-02	-2.10E-05	1.04E-07	5.24E-07	5.19E-06	0.94
Hospital	2.90E-03	5.36E-09	9.32E-04	-1.30E-07	-3.60E-03	8.68E-07	-1.80E-07	-3.79E-07	2.05E-07	1.00
Outpatient Healthcare	-1.23E-04	5.69E-08	2.64E-04	2.73E-09	6.77E-03	-2.30E-06	-2.21E-08	2.50E-07	-5.06E-07	0.99
Small Hotel	-1.53E-04	5.94E-08	1.04E-04	1.41E-08	-1.87E-04	2.51E-07	1.07E-08	2.52E-07	-1.67E-07	1.00
Large Hotel	-8.83E-04	2.85E-07	1.99E-03	-1.97E-07	-3.87E-03	5.51E-07	-1.01E-07	1.88E-06	9.40E-08	1.00
Primary School	3.04E-03	-1.10E-07	1.62E-03	-6.48E-08	2.10E-04	3.66E-07	-9.13E-08	-5.48E-07	-8.05E-07	0.98
Secondary School	-6.41E-03	5.91E-07	-1.58E-02	5.22E-07	3.51E-02	-1.61E-05	4.51E-07	1.96E-06	6.43E-06	0.91
Stand-Alone Retail	-2.13E-04	4.59E-07	7.97E-03	-3.61E-07	-2.03E-02	8.35E-06	-3.92E-07	2.31E-06	-2.54E-06	1.00
Strip Mall	-2.09E-03	4.35E-07	3.25E-03	-8.54E-08	-5.79E-03	3.14E-06	9.16E-08	2.02E-06	-1.60E-06	1.00
Warehouse	8.59E-04	9.97E-08	-5.79E-04	5.63E-08	2.71E-03	-8.13E-07	-7.00E-08	-1.37E-07	-5.34E-08	1.00

Table C4: Summary of coefficient for upgraded roof insulation gas savings for new construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	-3.05E-03	1.24E-06	-1.94E-02	9.33E-07	4.47E-02	-1.84E-05	3.86E-07	-1.26E-06	6.13E-06	1.00
Medium Office	-4.06E-03	3.94E-07	2.28E-04	-4.69E-08	4.42E-03	-1.74E-06	2.87E-07	1.12E-06	-1.67E-07	0.99
Large Office	-2.99E-04	7.36E-08	-8.30E-04	5.43E-08	4.86E-03	-1.72E-06	6.54E-08	1.07E-07	4.27E-08	1.00
Mid-rise Apartment	-4.58E-04	4.57E-07	-8.98E-03	1.87E-07	2.80E-02	-1.32E-05	3.73E-07	8.59E-07	4.05E-06	1.00
High-rise Apartment	8.70E-04	3.96E-08	-2.00E-03	-3.73E-08	2.42E-03	-2.23E-06	-1.35E-08	4.53E-07	1.60E-06	1.00
Quick Service Restaurant	-3.90E-04	9.65E-07	1.13E-02	-7.29E-07	-4.65E-02	1.82E-05	-5.67E-07	5.57E-06	-2.33E-06	0.99
Full Service Restaurant	7.77E-03	6.98E-07	-1.26E-02	7.33E-07	6.13E-03	-2.65E-06	-3.42E-07	4.30E-07	4.45E-06	0.99
Hospital	-4.42E-04	1.07E-07	-3.48E-03	2.79E-07	2.83E-02	-8.75E-06	4.19E-07	4.36E-07	-5.62E-07	0.99
Outpatient Healthcare	4.67E-03	-1.61E-07	-4.97E-03	2.47E-07	8.22E-03	-3.55E-06	-1.62E-07	-1.63E-06	1.77E-06	0.93
Small Hotel	4.32E-06	2.13E-10	3.66E-07	-5.15E-10	-1.56E-06	-3.65E-09	-3.59E-10	2.48E-09	3.17E-09	1.00
Large Hotel	-4.38E-03	1.64E-07	7.04E-03	-1.06E-07	2.21E-02	-3.66E-06	5.29E-07	2.56E-06	-5.19E-06	0.97
Primary School	-8.14E-03	1.16E-06	-1.04E-02	7.53E-07	5.77E-02	-1.62E-05	1.77E-06	6.62E-06	-3.71E-07	0.98
Secondary School	-3.87E-03	9.72E-07	-2.19E-02	1.18E-06	9.05E-02	-3.18E-05	1.40E-06	9.74E-07	3.50E-06	0.99
Stand-Alone Retail	5.13E-03	1.55E-06	-1.95E-02	5.34E-07	3.61E-02	-1.92E-05	1.24E-07	7.67E-07	9.61E-06	1.00
Strip Mall	-9.91E-03	2.36E-06	-3.49E-02	1.09E-06	8.13E-02	-3.82E-05	1.45E-06	3.81E-06	1.49E-05	1.00
Warehouse	3.40E-03	2.66E-07	-3.08E-03	9.92E-08	-5.37E-04	-1.28E-06	-1.61E-07	6.44E-07	2.15E-06	0.99

Table C5: Summary of coefficient for upgraded wall and roof insulation gas savings for new construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	-3.62E-03	1.76E-06	-2.85E-02	1.39E-06	6.49E-02	-2.66E-05	5.26E-07	-2.10E-06	9.02E-06	1.00
Medium Office	2.67E-03	1.14E-08	5.49E-03	-2.46E-07	-1.97E-02	7.68E-06	-3.46E-07	4.34E-07	-1.37E-06	0.99
Large Office	2.88E-04	1.48E-07	3.49E-03	-1.34E-07	-4.84E-03	2.43E-06	-8.60E-08	7.09E-07	-1.45E-06	1.00
Mid-rise Apartment	-2.57E-03	9.24E-07	-7.79E-03	2.08E-07	2.75E-02	-1.21E-05	4.75E-07	3.35E-06	2.96E-06	1.00
High-rise Apartment	-1.58E-03	3.23E-07	1.50E-03	-2.61E-07	-5.64E-03	6.53E-07	-4.74E-08	3.23E-06	7.95E-07	1.00
Quick Service Restaurant	-6.24E-04	2.00E-06	3.49E-03	-1.51E-07	-3.97E-02	1.62E-05	-8.92E-07	6.42E-06	-5.13E-07	0.99
Full Service Restaurant	-1.35E-03	1.35E-06	-3.74E-03	4.54E-07	-1.01E-02	5.59E-06	-8.86E-08	5.03E-06	4.02E-07	0.99
Hospital	7.34E-04	1.80E-07	-1.96E-03	1.24E-07	2.61E-02	-8.32E-06	3.14E-07	6.41E-07	-7.04E-07	1.00
Outpatient Healthcare	-1.47E-03	6.52E-08	-2.80E-04	-6.74E-09	1.20E-02	-4.42E-06	1.36E-07	7.12E-07	-3.20E-07	1.00
Small Hotel	-1.49E-04	5.99E-08	1.29E-04	1.24E-08	-2.44E-04	2.71E-07	9.49E-09	2.58E-07	-1.72E-07	1.00
Large Hotel	-6.48E-03	5.04E-07	8.97E-03	-2.43E-07	2.17E-02	-3.83E-06	5.01E-07	4.77E-06	-5.63E-06	0.99
Primary School	-9.75E-03	1.48E-06	-7.93E-03	5.86E-07	5.69E-02	-1.60E-05	1.72E-06	7.06E-06	-1.06E-06	0.98
Secondary School	-5.49E-03	1.22E-06	-1.47E-02	8.30E-07	8.09E-02	-2.74E-05	1.22E-06	2.24E-06	9.35E-07	0.99
Stand-Alone Retail	5.29E-03	2.01E-06	-1.53E-02	5.46E-07	3.29E-02	-1.59E-05	-5.76E-08	2.10E-06	6.63E-06	1.00
Strip Mall	-8.71E-03	2.65E-06	-3.15E-02	9.91E-07	7.37E-02	-3.46E-05	1.18E-06	4.95E-06	1.34E-05	1.00
Warehouse	2.74E-03	4.78E-07	-2.53E-03	9.23E-08	-4.35E-03	2.09E-07	-1.66E-07	1.53E-06	2.04E-06	0.99

Existing Construction

Table C6: Summary of coefficient for upgraded wall insulation electricity savings for existing construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	3.93E-03	2.62E-07	-8.13E-04	3.70E-08	2.04E-03	-1.05E-06	-2.60E-07	-1.47E-06	3.08E-07	0.97
Medium Office	-3.49E-03	-1.58E-07	1.35E-03	-9.63E-08	-3.46E-03	1.55E-06	3.98E-07	1.06E-06	-3.41E-07	0.98
Large Office	1.08E-03	6.90E-08	-3.77E-04	1.86E-08	9.50E-04	-4.77E-07	-9.33E-08	-3.47E-07	1.37E-07	0.94
Mid-rise Apartment	-4.78E-03	-1.05E-07	1.82E-03	-1.13E-07	-4.48E-03	2.11E-06	4.95E-07	1.47E-06	-5.64E-07	0.98
Quick Service Restaurant	-9.12E-03	-3.80E-07	3.07E-03	-2.00E-07	-7.75E-03	3.58E-06	9.30E-07	2.94E-06	-8.91E-07	0.98
Full Service Restaurant	-7.64E-03	-1.82E-07	1.88E-03	-1.16E-07	-4.79E-03	2.22E-06	6.63E-07	2.65E-06	-5.55E-07	0.98
Hospital	2.34E-03	1.91E-07	-1.30E-03	5.43E-08	3.13E-03	-1.63E-06	-2.10E-07	-7.55E-07	5.42E-07	0.95
Outpatient Healthcare	-9.00E-03	-2.56E-07	2.72E-03	-1.98E-07	-7.25E-03	3.21E-06	9.04E-07	2.87E-06	-6.37E-07	0.98
Small Hotel	-4.35E-03	-2.15E-07	1.90E-03	-1.15E-07	-4.33E-03	2.12E-06	5.00E-07	1.32E-06	-6.50E-07	0.96
Large Hotel	3.30E-05	3.21E-09	1.01E-04	-5.41E-09	-2.19E-04	1.20E-07	1.77E-08	-5.71E-08	-4.40E-08	0.98
Primary School	-2.21E-03	-2.90E-08	7.97E-04	-5.12E-08	-2.02E-03	9.32E-07	2.25E-07	6.72E-07	-2.32E-07	0.98
Secondary School	-3.07E-03	-6.66E-08	1.10E-03	-7.15E-08	-2.73E-03	1.25E-06	3.10E-07	9.55E-07	-3.17E-07	0.98
Stand-Alone Retail	8.10E-03	6.13E-07	-3.06E-03	1.69E-07	7.24E-03	-3.64E-06	-8.31E-07	-2.55E-06	1.12E-06	0.89
Strip Mall	-7.89E-03	-2.57E-07	2.72E-03	-1.74E-07	-6.73E-03	3.11E-06	7.78E-07	2.55E-06	-8.00E-07	0.99
Super Market	4.83E-03	3.53E-07	-2.01E-03	1.02E-07	4.65E-03	-2.42E-06	-5.00E-07	-1.49E-06	7.96E-07	0.94
Warehouse	-3.20E-04	6.21E-09	2.93E-04	-1.61E-08	-7.21E-04	3.58E-07	5.37E-08	4.12E-08	-1.02E-07	0.99

Table C7: Summary of coefficient for upgraded wall and roof insulation electricity savings for existing construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	4.00E-03	2.80E-07	-3.19E-04	1.42E-09	9.89E-04	-6.29E-07	-2.66E-07	-1.44E-06	1.90E-07	0.95
Medium Office	-2.37E-03	-7.54E-08	1.08E-03	-7.62E-08	-2.89E-03	1.32E-06	2.76E-07	6.76E-07	-2.66E-07	0.95
Large Office	1.24E-03	8.25E-08	-4.71E-04	2.43E-08	1.19E-03	-5.90E-07	-1.15E-07	-3.83E-07	1.66E-07	0.95
Mid-rise Apartment	-4.25E-03	-6.62E-08	1.59E-03	-9.88E-08	-3.94E-03	1.85E-06	4.25E-07	1.33E-06	-4.88E-07	0.98
Quick Service Restaurant	-4.32E-03	7.98E-08	1.26E-03	-7.25E-08	-3.62E-03	1.65E-06	3.15E-07	1.54E-06	-3.47E-07	0.96
Full Service Restaurant	-6.12E-03	1.44E-08	6.22E-04	-4.00E-08	-1.85E-03	7.63E-07	3.70E-07	2.48E-06	-1.20E-07	0.97
Hospital	3.09E-03	2.62E-07	-1.83E-03	8.14E-08	4.37E-03	-2.25E-06	-3.17E-07	-9.31E-07	7.38E-07	0.95
Outpatient Healthcare	-6.71E-03	-8.36E-08	1.99E-03	-1.57E-07	-5.84E-03	2.52E-06	6.51E-07	2.10E-06	-3.46E-07	0.96
Small Hotel	-6.19E-03	-3.93E-07	2.38E-03	-1.45E-07	-4.82E-03	2.44E-06	7.10E-07	1.99E-06	-8.83E-07	0.92
Large Hotel	2.33E-05	7.96E-10	7.68E-05	-4.84E-09	-1.56E-04	8.35E-08	1.66E-08	-4.14E-08	-3.41E-08	0.94
Primary School	5.04E-04	2.51E-07	-5.24E-04	2.67E-08	1.07E-03	-6.00E-07	-1.54E-07	-5.07E-08	2.35E-07	0.95
Secondary School	-1.12E-03	1.09E-07	2.48E-04	-2.26E-08	-7.39E-04	2.57E-07	5.78E-08	4.30E-07	-9.42E-09	0.97
Stand-Alone Retail	1.34E-02	1.13E-06	-3.42E-03	2.06E-07	7.65E-03	-3.86E-06	-1.41E-06	-4.49E-06	1.26E-06	0.83
Strip Mall	-5.45E-03	-7.73E-09	2.37E-03	-1.53E-07	-6.17E-03	2.73E-06	4.38E-07	1.84E-06	-6.08E-07	0.96
Super Market	8.55E-03	5.97E-07	-2.90E-03	1.71E-07	6.62E-03	-3.31E-06	-9.30E-07	-2.61E-06	1.07E-06	0.90
Warehouse	9.19E-05	4.43E-08	8.90E-05	-7.43E-09	-2.03E-04	8.23E-08	2.60E-09	-5.47E-08	-1.40E-08	0.98

Table C8: Summary of coefficient for upgraded wall insulation gas savings for existing construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	3.33E-03	-1.69E-07	-1.97E-03	-5.80E-08	-3.96E-04	-1.41E-06	-1.10E-07	-1.16E-06	1.91E-06	0.49
Medium Office	-1.32E-04	7.68E-09	2.20E-04	-9.28E-09	-4.04E-04	1.81E-07	1.86E-09	6.70E-08	-8.28E-08	0.99
Large Office	1.81E-03	-9.03E-08	-1.94E-03	1.37E-08	1.61E-03	-1.50E-06	-3.14E-08	-7.09E-07	1.31E-06	0.56
Mid-rise Apartment	3.25E-03	-1.73E-07	-1.08E-03	9.72E-09	-1.79E-03	-3.56E-08	-1.94E-07	-7.97E-07	9.95E-07	0.66
Quick Service Restaurant	9.18E-03	-4.48E-07	1.21E-04	2.56E-09	-1.16E-02	3.91E-06	-6.06E-07	-2.32E-06	7.42E-07	0.60
Full Service Restaurant	1.10E-03	-6.52E-08	4.46E-04	-4.68E-08	-2.30E-03	6.18E-07	-9.35E-08	-1.74E-07	1.39E-07	0.62
Hospital	3.83E-03	-1.73E-07	-6.47E-03	-6.89E-08	6.92E-03	-6.57E-06	-7.28E-08	-1.54E-06	5.00E-06	0.69
Outpatient Healthcare	4.73E-03	-1.91E-07	8.81E-03	-5.02E-07	-3.16E-02	1.14E-05	-8.50E-07	-2.79E-07	-1.00E-06	0.95
Small Hotel	5.24E-04	-2.75E-08	6.48E-06	-4.22E-09	-8.92E-04	2.70E-07	-3.52E-08	-1.00E-07	8.38E-08	0.75
Large Hotel	1.13E-03	-5.95E-08	-1.04E-03	5.83E-08	5.85E-04	-2.65E-07	-1.82E-08	-3.90E-07	3.67E-07	0.30
Primary School	3.02E-03	-1.67E-07	-7.13E-04	8.96E-09	-3.25E-03	7.52E-07	-1.84E-07	-7.32E-07	7.36E-07	0.72
Secondary School	2.09E-03	-1.17E-07	-3.87E-04	-5.74E-09	-2.53E-03	5.63E-07	-1.33E-07	-4.67E-07	5.27E-07	0.60
Stand-Alone Retail	3.81E-03	-1.92E-07	-2.45E-03	-6.91E-08	-2.09E-04	-1.83E-06	-1.25E-07	-1.32E-06	2.34E-06	0.50
Strip Mall	2.52E-03	-1.42E-07	-1.20E-03	5.27E-08	-1.37E-04	-2.03E-07	-1.06E-07	-6.81E-07	6.18E-07	0.79
Super Market	2.42E-03	-1.26E-07	-1.32E-03	-5.12E-08	-4.73E-04	-8.89E-07	-6.66E-08	-8.65E-07	1.33E-06	0.48
Warehouse	9.00E-04	-6.39E-08	-1.15E-04	2.05E-08	-1.34E-03	5.25E-07	-3.91E-08	-8.15E-08	7.62E-08	0.79

Table C9: Summary of coefficient for upgraded roof insulation gas savings for existing construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	7.65E-04	-5.45E-08	-1.82E-04	-3.98E-09	1.21E-03	-4.29E-07	-6.31E-09	3.66E-08	8.78E-09	0.96
Medium Office	-2.07E-05	-3.18E-09	2.84E-04	-1.48E-08	-5.21E-04	2.21E-07	-1.95E-09	3.44E-08	-9.51E-08	0.81
Large Office	-1.30E-05	-3.69E-09	-7.13E-05	1.94E-09	3.48E-04	-1.26E-07	8.69E-09	8.64E-09	1.05E-08	0.88
Mid-rise Apartment	3.44E-05	-3.01E-08	-1.18E-03	1.32E-08	4.47E-03	-1.94E-06	8.48E-08	-1.30E-07	4.56E-07	0.79
Quick Service Restaurant	1.33E-04	-3.97E-08	-7.18E-05	-7.11E-08	2.56E-03	-1.27E-06	5.26E-08	3.16E-07	1.98E-07	0.94
Full Service Restaurant	-4.32E-04	-4.00E-09	4.70E-06	-8.55E-08	3.55E-03	-1.77E-06	9.56E-08	2.92E-07	2.21E-07	0.95
Hospital	-2.54E-05	-1.28E-08	-1.71E-03	3.84E-08	5.01E-03	-2.18E-06	8.22E-08	-1.67E-07	6.75E-07	0.73
Outpatient Healthcare	-3.42E-04	1.84E-08	-4.19E-05	-8.22E-09	3.48E-04	-1.94E-07	2.87E-08	9.36E-08	4.35E-08	0.92
Small Hotel	-6.23E-05	3.45E-09	1.04E-04	-7.65E-09	-3.90E-04	1.27E-07	-4.49E-09	6.72E-08	-6.75E-09	0.96
Large Hotel	3.01E-04	-2.67E-08	-3.52E-04	3.31E-08	5.26E-04	-5.62E-08	2.38E-08	-9.90E-08	-1.33E-09	0.71
Primary School	4.12E-04	-8.21E-08	-5.11E-03	1.36E-07	1.41E-02	-6.07E-06	2.47E-07	-6.19E-07	1.89E-06	0.68
Secondary School	1.09E-03	-1.07E-07	-2.48E-03	8.48E-08	6.87E-03	-2.79E-06	7.27E-08	-4.55E-07	7.87E-07	0.80
Stand-Alone Retail	1.70E-03	-1.59E-07	-4.37E-03	2.15E-07	1.22E-02	-4.60E-06	1.36E-07	-7.71E-07	1.06E-06	0.87
Strip Mall	3.62E-04	-9.91E-08	-2.83E-03	1.19E-07	1.16E-02	-4.27E-06	1.83E-07	-3.41E-07	5.02E-07	0.85
Super Market	6.01E-04	-8.46E-08	-1.86E-03	1.07E-07	7.45E-03	-2.52E-06	1.02E-07	-2.96E-07	1.68E-07	0.88
Warehouse	-2.73E-04	5.49E-09	-2.86E-04	3.06E-08	8.89E-04	-6.11E-08	6.15E-08	1.45E-07	-1.35E-07	0.91

Table C10: Summary of coefficient for upgraded wall and roof insulation gas savings for existing construction

Building Type/Coefficients	a1	a2	a3	a4	a5	a6	a7	a8	a9	R^2
Small Office	3.91E-03	-2.18E-07	-1.88E-03	-6.23E-08	4.84E-04	-1.57E-06	-1.10E-07	-1.05E-06	1.73E-06	0.78
Medium Office	1.80E-03	-9.40E-08	-2.00E-03	1.56E-08	1.95E-03	-1.62E-06	-2.33E-08	-6.98E-07	1.31E-06	0.53
Large Office	-1.93E-04	6.62E-09	5.17E-04	-2.52E-08	-9.13E-04	3.98E-07	2.64E-09	1.13E-07	-1.82E-07	0.94
Mid-rise Apartment	3.30E-03	-2.03E-07	-2.23E-03	2.17E-08	2.59E-03	-1.95E-06	-1.14E-07	-9.24E-07	1.45E-06	0.82
Quick Service Restaurant	9.06E-03	-4.76E-07	1.71E-04	-8.10E-08	-9.11E-03	2.62E-06	-5.57E-07	-1.90E-06	9.48E-07	0.90
Full Service Restaurant	6.30E-04	-7.22E-08	4.29E-04	-1.30E-07	1.34E-03	-1.18E-06	9.16E-09	1.31E-07	3.57E-07	0.95
Hospital	3.89E-03	-1.91E-07	-7.98E-03	-2.68E-08	1.14E-02	-8.41E-06	-6.90E-10	-1.71E-06	5.54E-06	0.68
Outpatient Healthcare	4.23E-03	-1.64E-07	8.82E-03	-5.15E-07	-3.11E-02	1.11E-05	-8.11E-07	-1.49E-07	-9.74E-07	0.95
Small Hotel	4.25E-04	-2.16E-08	7.87E-05	-1.01E-08	-1.17E-03	3.55E-07	-3.70E-08	-2.68E-08	8.34E-08	0.90
Large Hotel	1.55E-03	-9.21E-08	-1.46E-03	9.18E-08	1.02E-03	-3.26E-07	-5.77E-10	-5.20E-07	4.24E-07	0.58
Primary School	3.16E-03	-2.29E-07	-6.40E-03	1.71E-07	1.27E-02	-6.06E-06	8.82E-08	-1.35E-06	2.80E-06	0.69
Secondary School	3.08E-03	-2.19E-07	-2.96E-03	8.60E-08	4.64E-03	-2.33E-06	-5.60E-08	-9.03E-07	1.33E-06	0.80
Stand-Alone Retail	5.03E-03	-3.27E-07	-7.16E-03	1.61E-07	1.38E-02	-7.05E-06	6.51E-08	-2.04E-06	3.42E-06	0.72
Strip Mall	2.96E-03	-2.46E-07	-4.24E-03	1.89E-07	1.19E-02	-4.61E-06	7.82E-08	-1.06E-06	1.15E-06	0.89
Super Market	2.88E-03	-2.03E-07	-3.15E-03	4.58E-08	7.13E-03	-3.51E-06	4.15E-08	-1.12E-06	1.52E-06	0.75
Warehouse	1.43E-03	-9.82E-08	-5.17E-04	5.74E-08	-1.17E-03	6.88E-07	-2.76E-08	-1.65E-07	3.86E-08	0.90

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