Life Cycle Assessment of Spray Polyurethane Foam Insulation

for Residential & Commercial Building Applications

Prepared by: SPFA Spray Polyurethane Foam Alliance

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Acronyms & Abbreviations

AP	Acidification potential
ccSPF	Closed-cell SPF (also called "medium-density" or "two pound" spray foam; called "3 pound" spray foam for roofing applications)
CO_2-eq	Carbon dioxide equivalents (greenhouse gas emissions)
EP	Eutrophication potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing); LCA database and software from PE International
GHGs	Greenhouse gases
GWP	Global warming potential
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MDI	Methylene diphenyl diisocyanate
MJ	Mega joules (106 Joules)
ocSPF	Open-cell SPF (also called low-density or "half pound" spray foam)
ODP	Ozone depletion potential
POCP	Photochemical Ozone Creation Potential, a characterization factor for the impact category of Photochemical Ozone Creation or Photochemical Smog Creation
R	R-value or thermal resistance of an insulation material, based on the U.S. or Imperial unit system ($h \cdot ft^2 \cdot °F/Btu$)
RSI	R-value or thermal resistance of an insulation material, based on the metric or International System, SI ($K \cdot m^2/W$)
SCP	Smog creation potential
SPF	Spray polyurethane foam
SI	International system of units (metric) used globally
IP	Inches, pounds, etc., used in the United States

Note on terminology: Climate change is the technically correct term for the Impact Category measured using GWP (characterization factor) for specific GHGs (e.g., carbon dioxide, methane, nitrous oxide). However, in some cases GWP or GHGs are noted in the text, plots, and tables as these terms are commonly used to indicate climate change.

Executive Summary

LCA Goals and Scope

The Spray Polyurethane Foam Alliance (SPFA) initiated a life cycle assessment (LCA) of spray foam insulation to evaluate the environmental footprint of spray polyurethane foam (SPF) formulations used in residential and commercial building applications. This pioneering study is the first comprehensive LCA of spray foam insulation conducted in North America. Unlike limited LCAs that exclude the impacts of using a product, this cradle-to-end of life study includes scenarios of spray foam use for residential and commercial applications in three U.S. climate zones. Moreover, the study is based on current operations data from spray foam formulators and installers and has been critically reviewed by a panel of independent LCA, insulation industry, and building science experts.

The goals of the LCA are to better understand the impacts across the life cycle of various foam formulations, to promote the benefits of spray polyurethane foam insulation with data based on rigorous assessment methodology, and to create publically available industry averages for selected spray foam products. The primary audience for this study is the building and construction community and users of publicly available life cycle inventories in North America.

This is a full and detailed LCA with complete boundaries and key environmental impact categories included in the assessment. Spray foam insulation is evaluated from cradle-to-end of life, including relevant scenarios that demonstrate the benefits of spray foam insulation in the building use phase. The study covers primary energy from non-renewable resources, plus five environmental impacts related to air/water pollution: climate change (carbon footprint), acidification, eutrophication, ozone depletion, and smog creation.

New Residential Construction

When open-cell spray foam is installed on 2,500 ft^2 residential houses in Houston (Climate Zone 2), Richmond (Climate Zone 4), and Minneapolis (Climate Zone 6), energy savings versus no cavity insulation during a 60 year service life are from 64 to 194 times greater than the embodied energy in the open-cell foam.

The results for the much denser closed-cell insulation yield energy saved to energy embodied ratios that are half as much as energy savings in these climate zones range from 32 to 98 times greater than the closed-cell embodied energy.

It should be noted that the other inherent benefits of closed-cell insulation, such as its integrated vapor retarder (required by building codes in colder climates), water resistance, and added structural performance, are not included in this analysis. For the purposes of this analysis, SPF was assumed to be applied between structural members. If used as continuous insulation on the exterior of the home, there would be additional benefit from the SPF by eliminating thermal breaks.

Climate change results (greenhouse gases or GHGs), however, show GHG avoided benefits but even greater differences in open-cell versus closed-cell foam. The GHG avoided to embodied ratios for open-cell foam in residential houses in these zones range from 92 to 248, whereas the GHG avoided to GHG embodied ratios for closed-cell foam range from approximately 8 to 21. The closed-cell foam GHG avoided to GHG embodied ratios are about a dozen times less compared to open-cell foam, mainly due to the high GWP blowing agent currently used to make closed-cell foam.

Regarding other environmental impacts avoided (acidification, eutrophication, ozone depletion, and smog creation) for residential housing, the impacts avoided to embodied ratios for open-cell foam range from 44 to 134 (Houston) and 40 to 159 (Minneapolis). For closed-cell foam, the ratios are similar to those observed for energy: approximately half compared to open cell as result of greater embodied impacts associated with the denser closed-cell foam.

Commercial Building Roof Retrofits

While the life cycle impacts for new residential construction were evaluated, existing commercial buildings were evaluated for roofing retrofits. For roofing spray foam installed to obtain an R20 retrofit on a 22,500 ft^2 strip mall, energy savings in Houston, Richmond, and Minneapolis during the 60 year service insulation life range from 55 to 66 times greater than the baseline of R4. The results for an R12 baseline to an R20 retrofit yield energy saved to energy embodied ratios in these cities about 30 times greater than the baseline. As expected, the energy savings to energy embodied ratios for the R12 baseline case are half of that compared to the R4 baseline, but nevertheless significant.

Climate change results show a similar trend, with ratios of use phase GHG avoided to embodied ranging from 15 to 17 for an R4 to R20 retrofit and ratios of use phase GHG avoided to embodied ranging from 7 to 8 for an R12 to R20 retrofit.

Other environmental impacts for the commercial building show similar but more pronounced trends resulting from higher impacts associated with electricity use in Climate Zone 2 (Houston), as use phase impacts avoided to embodied impacts range from 30 to 106 (Houston) and 20 to 71 (Minneapolis) for an R4 to R20 retrofit, and 16 to 57 (Houston) and 9 to 31 (Minneapolis) for an R12 to R20 retrofit.

Use Phase Dominates

Results show that energy and environmental benefits from spray foam insulation use in new residential construction and commercial roofing retrofits far outweigh the embodied energy and embodied environmental impacts, that is, the energy and impacts "invested" to make, install, transport, and dispose of the insulation at end of life are minimal compared to the use phase benefits. Variations in the ratios and payback periods for energy savings and environmental impacts avoided result mainly from type of spray foam applied, different climate zones, and type of energy used (electricity versus natural gas). However, in all cases the energy savings and environmental impacts avoided during spray foam use overwhelm the embodied energy and embodied environmental impacts. Rigorous life cycle assessment methodology and whole building energy simulation modeling confirm that the use phase dominates the life cycle. Spray foam insulation's high thermal resistivity combined with low air infiltration is an exceptional material for saving energy and reducing environmental impacts over the life of a building.

1 Introduction

This study was conducted in two distinct but related parts to determine the environmental impacts of all spray foam life cycle phases:

- Embodied phases: spray foam raw materials and blending, transportation, installation, and end of life. Embodied phases are assessed according to ISO LCA standards (ISO 14040, 2006; ISO 14044, 2006) methodology, which define the embodied phases goal and scope, inventory analysis, impact assessment, and interpretation.
- Use phase: spray foam insulation during its service life in new residential houses and commercial building roofing retrofits. The use phase is evaluated with whole building energy simulation tools: RESNET-approved software (EnergyGauge) for residential and U.S. Department of Energy software (U.S. DOE EnergyPlus) for commercial.

Section 2 of this report covers the methodology and results for the embodied phases while Sections 3 and 4 focus on use-phase applications and results. Section 5 combines the embodied and use-phase results for a complete life cycle picture and Section 6 provides conclusions.

The embodied phase study was conducted by PE International, Inc., while the use phase simulation studies on residential and commercial structures were performed by Sustainable Solutions Corporation. This report is based on three studies developed by LCA/building science consultants commissioned by SPFA:

- *Life Cycle Assessment of Spray Polyurethane Foam Insulation Products*, prepared for SPFA by PE International, Inc. (February 3, 2012)
- *SPF Residential Energy Modeling Analysis*, prepared for SPFA by Sustainable Solutions Corporation (March 15, 2012)
- *SPF Commercial Energy Modeling Analysis*, prepared for SPFA by Sustainable Solutions Corporation (March 15, 2012)

In order to verify conformance with globally-recognized standards for LCA (ISO 14040/14044) and strengthen the credibility of this study, SPFA commissioned critical reviews of all three studies. The report on *Life Cycle Assessment of Spray Polyurethane Foam Insulation Products* was reviewed according to the critical review requirements of ISO 14040/44 by independent LCA/insulation industry experts. A letter confirming this review, dated June 22, 2012, is included in the PE International Report.

The Critical Review Panel included the following members:

- Dr. Deanna Matthews, panel chair and LCA expert, president of Avenue C Advisors
- Dr. Jonathan Maynes, polyurethane chemist, Rigid Foam Team Leader for Evonik Industries
- Mr. Roger Morrison, P.E., RRC, spray foam expert, president of Deer Ridge Consulting, Inc.

Similarly, the reports on *SPF Residential Energy Modeling Analysis* and *SPF Commercial Energy Modeling Analysis* were reviewed by independent building science experts with input and direction from Ms. Lois B. Arena, Senior Building Systems Engineer, Steven Winters Associates, Inc. A copy of the letter from Steven Winter Associates, Inc., confirming this independent building science review of the energy modeling analysis, is available upon request from SPFA.

The three studies are available through SPFA upon request and include further details as well as signed review statements regarding the technical correctness/quality of the studies. The remainder of this report consolidates relevant information on the embodied and use phase studies with a focus on the complete spray foam insulation life cycle. This LCA report has been verified to be in accordance with ISO 14025, the UL Environment EPD Program Operator Rules, and the UL Environment Product Category Rule for Building Envelope Thermal Insulation Version 1.1.

2 Embodied Phases: LCA Goal and Scope

2.1 Purpose and Audience

The purpose of the embodied phases study is to understand the environmental impacts of spray polyurethane foam (SPF) from cradle-to-end of life on a product level according to ISO 14040/ISO 14044. The product level means that life cycle impacts from the building use level (reduction in energy and environmental impacts due to the presence of insulation) are not covered. The impacts from a building use level are determined using whole building energy simulation modeling, as documented in Section 4 of this report.

The results of this section are primarily intended for use in North America by the building and construction community and users of publicly available life cycle inventories. These results address all emissions covered in the U.S. EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2.0) methodology. The study considers cradle-to-end of life environmental impacts of spray foam on a product level in both commercial and residential applications as well as their final end of life treatment. The three specific products considered are low-density (open cell or ocSPF) and medium-density (closed-cell or ccSPF) foams for use in wall cavities plus closed-cell foam used in roofing applications.

Primary data for embodied phases were collected from six formulation locations, literature provided by chemical suppliers, and six installation contractors to attain an industry average of energy and material usage. Best available data (representative of technology, geographical area, recent information, etc.) were used for all upstream raw materials.

2.2 System Boundaries

Figure 2-1 shows the life cycle stages associated with the embodied phase study, which focuses only on the spray foam insulation in a building as it excludes all other building materials. As shown in the figure below, "SPF Use and Maintenance" includes only the impacts of blowing agent lost to the environment during spray foam use on a building. The effects of spray foam insulation on the thermal resistance of the building envelope (i.e., energy savings and environmental impacts avoided during insulation use) are covered in Sections 4 and 5 of this report.

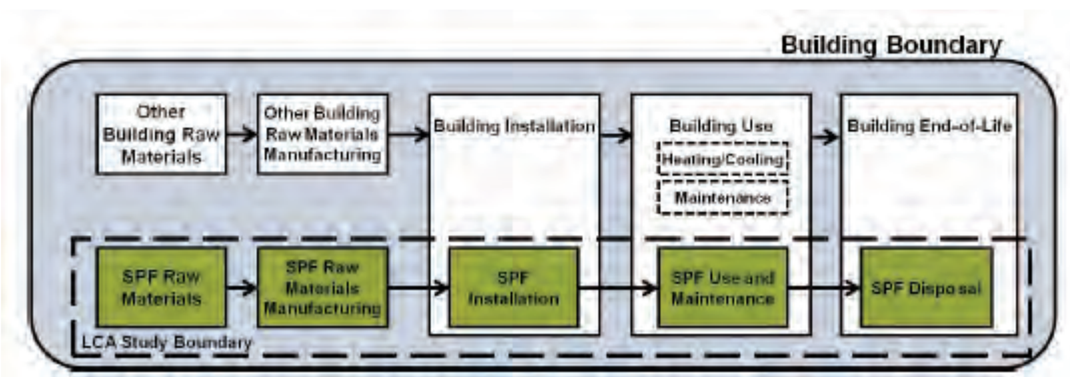


Figure 2-1 Life cycle flow diagram of SPF insulation products

Included in the embodied phases are upstream processing and production of materials and energies needed for the production of SPF, transport of materials (all chemical inputs for production and packaging) to SPF insulation formulation sites, formulation of SPF components, transport of the components to the installation site, installation, removal, and transport of insulation to disposal site, and end of life disposal in a landfill. Table 2-1 summarizes what is included in and excluded from the embodied phases study.

Table 2-1 Embodied Phases System Boundaries

INCLUDED	EXCLUDED
✓ Extraction of raw materials ✓ Production and manufacturing of raw materials for spray foam and packaging ✓ Spray foam formulation ✓ Spray foam installation ✓ Spray foam use phase emissions ✓ End of life of insulation and packaging ✓ Transportation between all life cycle stages	× Construction of capital equipment × Maintenance of support equipment × Human labor and employee commute × Energy savings and environmental impacts avoided from product use

2.3 Functional Unit

The functional unit is based on providing thermal insulation for building envelopes, as defined by the Product Category Rule (PCR) for Building Envelope Thermal Insulation, Product Category Rule Number UL 110116 (UL Environment, 2011): 1 m^2 of insulation material with a thickness that gives a design thermal resistance $R_{SI} = 1\ m^2{\cdot}K/W$ ($R_{IP} = 5.68\ h{\cdot}ft^2{\cdot}°F/Btu$) and with a building service life of 60 years. The standard unit of measurement for spray foam insulation is a board foot (bd ft), which is 1 ft^2 of insulation that is 1 inch thick.

To achieve 1 m^2 with a thickness that provides $R_{SI} = 1$, the different foam products require unique reference flows. The reference flows are needed as a basis for performing the life cycle calculations as these defined volumes can be converted to mass values. The thickness required to provide $R_{SI} = 1$ is calculated by dividing the target R-value defined in the functional unit above by the foam's R-value. For the purposes of this report and dataset generation, representative R-values given by SPFA are used. Reference flows (i.e., defined area and thickness to be converted to mass for subsequent calculations) for the three foam products are shown below:

Table 2-2 Reference Flows – 1 m^2 with Specified Thicknesses

	UNITS	LOW-DENSITY OPEN-CELL	MED-DENSITY CLOSED-CELL	ROOFING CLOSED-CELL
Target R-Value	[h·ft²·°F/Btu]	5.68	5.68	5.68
Foam R-Value	[h·ft²·°F/Btu] per inch	3.6	6.2	6.2
Thickness	[inches]	1.58	0.92	0.92

SPF is created by mixing equal volumes of two chemicals, commonly referred to as A-side and B-side. A-side is the industry term for the isocyanate component of foam, in this case polymeric methylene diphenyl diisocyanate (pMDI). This study used a dataset representing North American MDI products from the GaBi 5 database. This MDI dataset was based on a study commissioned by the American Chemistry Council (ACC) and conducted by Franklin Associates. This same dataset was used in the PIMA polyiso LCA (Phelan et al., 2011).

The "B-side" is a mixture of polyols, fire retardants, blowing agents, catalysts, and other additives that, when mixed with "A-side," creates foam that can be applied for insulation. As the formulation of this B-side mixture may vary with each company producing SPF chemicals, this study uses generic formulations based on spray foam industry input. A total of five different formulations were studied, three based on SPFA member input and two (for low and medium-density foam) based on those provided by CPI. Table 2-3 shows the three representative formulations based on SPFA members as these are used throughout this report as a basis for the embodied phases and subsequent life cycle impact calculations. The formulations based on SPFA ("Low-Den 1" and "Med-Den 1") are noted, as results comparing these to formulations from CPI ("Low-Den 2" and "Med-Den 2") are provided in later sections of this report.

Table 2-3 Spray Foam Formulations

CHEMICAL	LOW-DENSITY (LOW-DEN 1)	MEDIUM-DENSITY (MED-DEN 1)	ROOFING
Polyol – Polyester	-	45.0%	35.0%
Polyol – Mannich	-	30.0%	45.0%
Polyol – Compatibilizer	10.0%	-	-
Polyol – Polyether	35.0%	-	-
Fire Retardant – TCPP	25.0%	4.0%	8.0%
Fire Retardant – Brominated	-	6.0%	-
Blowing Agent – Reactive (H2O)	23.5%	2.0%	1.6%
Blowing Agent – Physical (HFC)	-	8.5%	7.0%
Catalyst – Amine	6.0%	3.0%	2.0%
Catalyst – Metal	-	0.5%	0.4%
Surfactants – Silicone	0.5%	1.0%	1.0%

The density of the foam is calculated based on the specific gravity of open and closed-cell foams, combined with installers' reported volume blown. Based on industry MSDS data for 2.0 lb/ft^3 closed-cell and 0.5 lb/ft^3 open-cell SPF systems, the reported specific gravity for the A-side, closed-cell B-side (medium-density and roofing), and open-cell B-side (low-density) are 1.22, 1.17, and 1.10 respectively. Because 55 gallon drums of each A and B-side are used, the total weights of foam ingredients typically used are shown below. Based on industry safe practices and input on drum filling, 51 gallons is the amount of material typically contained in a drum. Table 2-4 shows the material weights, converting the specific gravities using a density of water at 8.33 lb/gal:

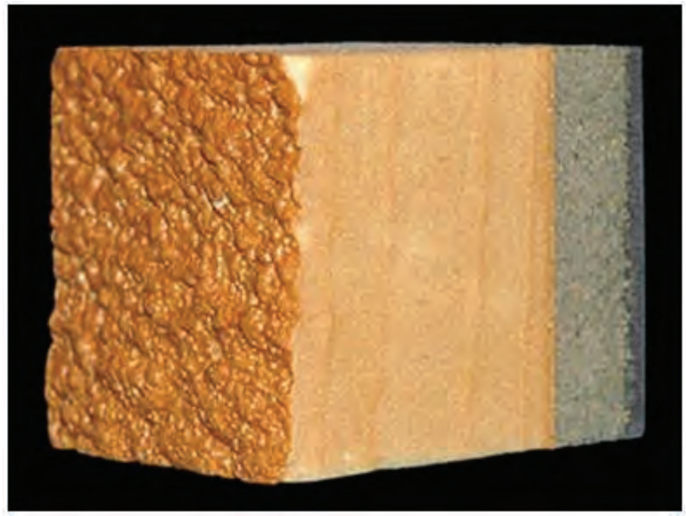


Figure 2-2 Cross-section of spray foam insulation with layers of various densities (collectSPACE.com)

Table 2-4 Calculated Weights of Foam Ingredients

	LOW-DENSITY	MEDIUM-DENSITY AND ROOFING
A-side	1.22 x 8.33lb/gal x 51 gal = 518 lb	1.22 x 8.33lb/gal x 51 gal = 518 lb
B-side	1.1 x 8.33 lb/gal x 51 gal = 467 lb	1.17 x 8.33lb/gal x 51 gal = 497 lb
Total Drum Set	518 + 467 = 985 lb	518 + 497 = 1015 lb

Using the reported volume of foam achieved by installers for each type of product, the density is calculated with the following formula:

$$calculated\ density\ \left[\frac{lbs}{ft^3}\right] = \frac{drumset\ weight\ [lbs]}{foam\ volume\ [bd\ ft]} \times \frac{1\ [bd\ ft]}{1[ft^2\ in]} \times \frac{12\ [in]}{1[ft]}$$

This calculated density is slightly higher than the actual density because losses occur during foaming. Water vapor, CO_2, and HFC blowing agent are released when the liquid ingredients combine. The mass of HFC escaping is simply calculated by multiplying the HFC content of the foam with the assumed rate of emission at installation.

CO_2 is also liberated as a result of the reaction between water and isocyanate. This mass is calculated differently for closed versus open-cell foams. In the case of closed-cell foams, all the B-side water reacts with isocyanate. The molar ratio of CO_2 to water is 44 / 18 or 2.44, so assuming that the B-side formulation contains 1.75% water, 497 lbs of B-side (as calculated above) would yield 0.021 lbs CO_2 / lb ingredients or 2.1% loss.

In the case of open-cell foam, only a fraction of water reacts with isocyanate. Typically, half pound or low-density SPF is formulated with an excess of water in the B-side beyond what is needed for reaction. Generally speaking, about 25-35% of the water is consumed by reaction with isocyanate and the rest is available for conversion to steam during the exothermic foaming process.

For example, if the B-side formulation contains 17.5% water and 25% of it reacts, 467 lbs of B-side would yield 0.051 lbs CO_2 / lb ingredients or 5.1% loss.

Both the yield losses calculated above and installation trim scrap increase the raw materials and processing upstream needed to achieve the specified 1 m^2 with a thickness that provides R_{SI} = 1, so the mass calculation is scaled upward to account for these losses. Average installed volume and scrap losses are based on surveys and input from spray foam installers.

It is assumed that the thermal resistance increases in a fixed ratio with foam thickness and thus the mass of foam for each reference flow can be calculated using the following formula:

$$mass\ [lbs] = A\ [ft^2] * thickness\ [in] * \frac{1\ [ft]}{12\ [in]} * \rho \left[\frac{lbs}{ft^3}\right] * \frac{1}{(1 - yield\ loss) * (1 - scrap)}$$

where:

- A is the area of the foam being measured, in this case 1 m^2 or 10.764 ft^2
- thickness is calculated by dividing the target R-value by the R-value per inch of the foam
- ρ is the actual density of the foam in lbs/ft^3
- yield loss is the fraction that accounts for the loss of mass when liquid is foamed
- scrap is the fraction that accounts for trim losses during installation

As noted previously, to achieve 1 m^2 with a thickness that provides R_{SI} = 1, the different foam products require unique reference flow mass values. The reference flows and physical properties are shown in Table 2-5.

Table 2-5 Mass Values and Intermediate Calculations of Reference Flows

	UNITS	LOW-DENSITY OPEN-CELL	MED-DENSITY CLOSED-CELL	MED-DENSITY ROOFING
Thickness	[inches]	1.58	0.92	0.92
Nominal Density	[lbs/ft^3]	0.5	2.0	3.0
Average Installed volume	[bdft/drumset]	14000	4100	2800
p (actual density)	[lbs/ft^3]	0.84	2.97	4.35
Yield Loss	[wt. fraction] 0 – 1	0.05	0.03	0.03
Scrap	[wt. fraction] 0 – 1	0.08	0.04	0.02
Mass	[lbs]	1.31	2.55	3.67

2.4 Data Inventory Sources

Primary data were collected from six formulation locations and six installation contractors. In addition to primary data, the model utilizes GaBi 5 background data.

2.4.1 Fuels and Energy – Background Data

National averages for electricity grid mixes are from the GaBi 5 database. For each of the formulation manufacturers and for spray foam installation, the most recent U. S. national average energy data from the GaBi 5 database are used.

2.4.2 Raw and Process Materials – Background Data

Data were collected and modeled to ensure that:

- All materials are modeled according to the same boundary conditions
- The analysis is free of biases regarding different background/upstream systems
- The results represent current technology/technology mixes

Table 2-6 shows the sources of data that were collected, the data used from existing databases, or data from published studies.

Table 2-6 Data Sources

DATA REQUIRED	DATA SOURCE
FORMULATION	
Materials	
Polyol – Polyester	Dataset from PIMA Study (Phelan et. al., 2011)
Polyol –Mannich	Created from combination of Dow (U.S. Patent 6,281,393 B1, 2001) and Huntsman (U.S. Patent 6,495,722 B1, 2002) patents
Polyol – Compatibilizer	GaBi 5 database
Polyol – Polyether	US: Polyethylene glycol PE (proxy)
Fire Retardant – TCPP	GaBi 5 database
Fire Retardant – Brominated	US: Polyether polyol (from PO+EO) PE
Blowing Agent – Reactive	GaBi 5 database
Blowing Agent – Physical	US: Tris(2-chloroisopropyl)phosphate (TCPP) PE
Catalyst – Amine	Created from combination of two Ethyl Corporation patents (U.S. Patent 4,468,480, 1984; U.S. Patent 4,564,697, 1986)
Catalyst – Metal	GaBi 5 database
Surfactants – Silicone	US: De-ionized water (reverse osmosis/electro ion) PE
pMDI	Created from McCulloch 2010 (McCulloch, 2010)
Energy	GaBi 5 database
	DE: Trimethylamine by-product di-, monomethylamine PE (proxy)
	Internal data development
	GaBi 5 database
	DE: Siloxane (cyclic) (made of organic silane) PE
	Dataset from ACC Study (American Chemistry Council, 2011)
	Primary data collected from formulators
Installation	
Materials	Primary data collected from installation contractors
Energy	Primary data collected from installation contractors
End of Life	GaBi 5 database Europe: Landfill for inert matter, includes leachate treatment (unspecific construction waste) PE

2.4.3 Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials to formulation facilities as well as to the construction site and disposal at end of life.

The GaBi 5 database was used to model all transportation and fuel production. Truck transportation within the United States was modeled using the GaBi U.S. truck transportation datasets. The vehicle types, fuel usage, and emissions for these transportation processes were developed using a GaBi model based on the most recent U.S. Census Bureau Vehicle Inventory and Use Survey (2002) and U.S. EPA emissions standards for heavy trucks in 2007.

2.4.4 Allocation

As most spray foam formulators create more than just the chemicals needed for spray foam, mass allocation of the facility's total life cycle inventory was performed based on the annual output mass of the products created.

Allocation of upstream data (energy and materials) in the GaBi 5 database is as follows:

- For all refinery products, allocation by mass and net calorific value is applied. The manufacturing route of every refinery product is modeled and so the effort of the production of these products is calculated specifically. Two allocation rules are applied: 1) the raw material (crude oil) consumption of the respective stages, which is necessary for the production of a product or an intermediate product, is allocated by total energy based on the calorific value of the product; and 2) the energy consumption (thermal energy, steam, electricity) of a process (e.g., atmospheric distillation) being required by a product or an intermediate product are charged on the product according to the share of the throughput of the stage (mass allocation).
- Materials and chemicals needed during manufacturing are modeled using the allocation rule most suitable for the respective product. For example, the major raw material used to produce spray foam, pMDI, was developed in the ACC study using mass allocation by assigning environmental burdens (energy, GHGs, etc.) to the product (pMDI) and its co-product (HCl). Further information on a specific product is available from GaBi documentation (PE International Software, 2012).

2.4.5 Emissions to Air, Water, and Soil

All process emissions reported by the formulators for the manufacturing phase are taken into account in the study. If there were data missing in response to initial surveys, PE International, Inc., engaged with the companies to obtain the data. All gate-to-gate emissions data were obtained from the formulators.

Upstream data for all raw materials, electricity, and energy carriers were obtained from the 2011 release of the GaBi 5 database. Emissions (CO_2, etc.) due to the use of electricity are accounted for with the use of the database processes.

Emissions associated with transportation were determined by applying the logistical details of involved companies (data collected from the companies for the reference year applied to transportation models from the GaBi 5 database).

2.4.6 Cut-Off Criteria

The cut-off criteria used for including or excluding materials, energy, and emissions data of the study are as follows:

- Mass: If a flow is less than 1% of the cumulative mass of the model it may be excluded, providing its environmental relevance is not a concern.
- Energy: If a flow is less than 1% of the cumulative energy of the model it may be excluded, providing its environmental relevance is not a concern.
- Environmental relevance: If a flow meets the above criteria for exclusion yet was identified by LCA experts as a potentially relevant contributor, a proxy LCI with conservative environmental burdens was chosen (high burden per unit compared to typical ingredients). If the proxy datasets exceed the 1% individual cut-offs, additional research or justification is necessary.

The sum of the excluded material flows did not exceed 5% of mass, energy, or environmental relevance.

2.5 Data Quality

2.5.1 Representativeness

Efforts were made to use representative data for the embodied phases associated with spray foam manufacturing, formulation, transportation, installation, and end of life in North America as follows:

- Technology: In the study, representative formulas based on SPFA and production technologies for U.S. manufacturing/formulation of the spray foams are used. Profiles from the GaBi 5 Software Database are utilized for other ancillary or process materials such as the production of chemical stock, fuels, power, and regional grid mixes. Access to the most recent U.S. datasets for polyester polyol and pMDI was granted through permission of the manufacturers or associations which have recently completed life cycle assessments of their products (Phelan et al., 2011).
- Time Period: Installation and formulation data were collected from 2010 yearly totals. Secondary data for most primary material components is from 2006 or more recent.
- Geography: The geographical coverage of this study is spray foam insulation manufacturing and installation in North America. Due to data availability and quality, U.S.-based datasets are used in the model where appropriate.

2.5.2 Other Data Quality Indicators

As covered in the embodied phases report (PE International Inc., 2012), data development considered precision, completeness, consistency, and reproducibility of life cycle inventory information.

2.6 Embodied Phases Life Cycle Impact Assessment Results

Table 2-7 shows an overview of the impacts. The results are displayed for 1 m^2 of insulation material with a thickness that yields RSI = 1. The "Low-Den 1," "Med-Den 1," and "Roofing" are based on the formulation data from SPFA. The "Low-Den 2" and "Med-Den 2" are based on formulations from CPI (CPI 2010 – Generic formulations for high-pressure, low-density and medium-density SPF used by the American Chemistry Council Center for the Polyurethane Industries (CPI) concurrent emissions and exposure studies), which are not used in subsequent use-phase energy savings and impacts avoided calculations in section 5 of this report but are provided here for comparison. It is worth noting that the life cycle impacts summarized in Table 2-7 are very similar for both the SPFA and CPI formulations.

Table 2-7 Overview of Life Cycle Impacts per Reference Flow (1 m^2, R_{SI}=1), Embodied Phases

DATA REQUIRED	LOW-DEN 1	LOW-DEN 2	MED-DEN 1	MED-DEN 2	ROOFING
REFERENCE FLOWS					
Mass [lbs]	1.31	1.31	2.55	2.55	3.67
Thickness [inches]	1.58	1.58	0.92	0.92	0.92
Life Cycle Impacts per Reference Flow					
Primary Energy from Resources [MJ]	50.5	51.3	94.8	95.5	136.7
Climate Change[kg CO_2-Equiv.]	2.4	2.4	27.6	23.7	34.3
Acidification [kg H^+ moles-Equiv.]	0.396	0.399	0.780	0.755	1.073
Eutrophication [kg N-Equiv.]	4.33E-04	4.39E-04	8.99E-04	9.11E-04	1.33E-03
Ozone Depletion [kg CFC 11-Equiv.]	6.59E-08	6.70E-08	1.15E-07	1.18E-07	1.67E-07
Smog Creation [kg O_3-Equiv.]	0.094	0.095	0.180	0.185	0.267

Figure 2-3 below shows the normalized impacts of spray foam across all embodied life cycle phases for TRACI 2.0 impact categories considered. It is calculated by taking the impacts per product and dividing them by the U.S. statistical yearly emissions. Normalizing the results is optional per ISO 14044 but is shown to identify the impacts with relatively higher values.

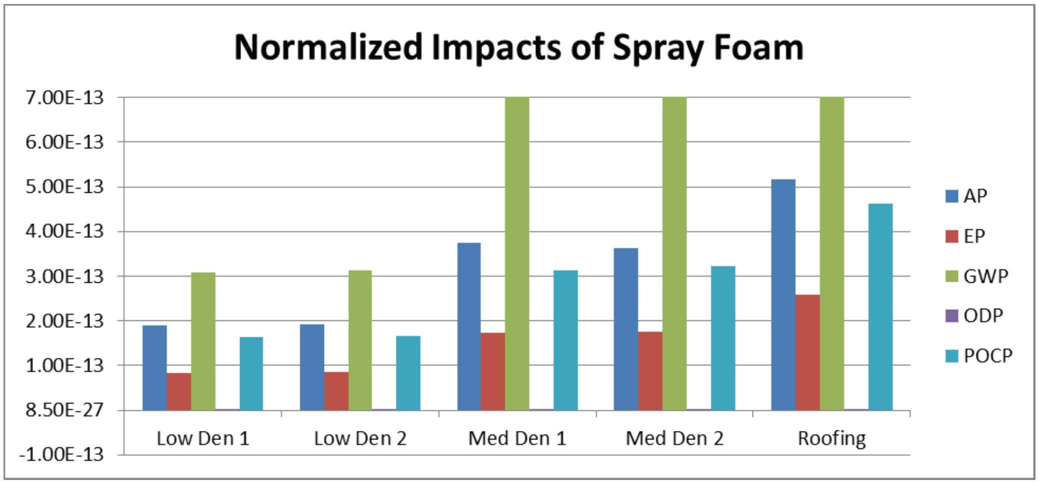


Figure 2-3 Normalized impacts of spray foam (1 m^2, R_{SI}=1), embodied phases

GWP values for Med-Den 1, 2, and Roofing are 3.57E-12, 3.05E-12, and 4.43E-12, respectively

The bars for the global warming potential of the closed-cell and roofing foams are much higher than the rest of the impacts due to the emissions of the blowing agent HFC-245fa. This normalization also shows that ozone depletion potential is a negligible impact compared to the others. Because energy and GWP aspects are typically of greatest interest to most stakeholders, Figures 2-4 and 2-5 below show the Primary Energy Demand and Global Warming Potential by embodied phases of the life cycle.

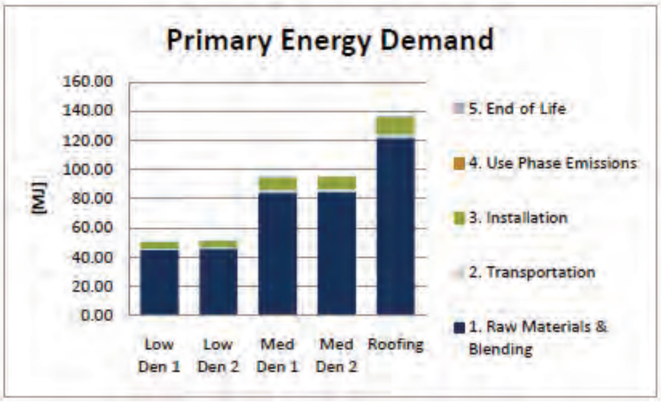


Figure 2-4 Primary energy demand by embodied life cycle phase (1 m², R_{SI}=1)

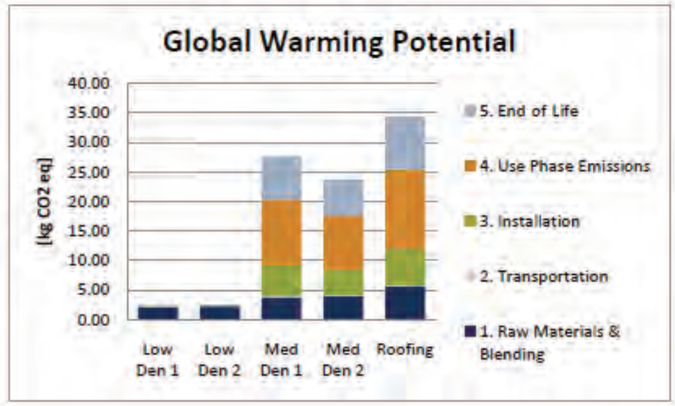


Figure 2-5 Global warming potential by embodied life cycle phase (1 m², R_{SI}=1)

For medium-density and roofing foams, the release of the blowing agent HFC-245fa contributes approximately 85% of the global warming potential in the embodied phases. Because this emission has such a large effect on GWP and because blowing agent emissions are fairly uncertain, sensitivity analysis was used to evaluate the effects of different blowing agent loss rates on the product footprint related to the embodied phases.

For the low-density foams, and for the other impact categories considered for medium-density and roofing foams (non-GWP), about 90% of the embodied phase impacts are related to upstream raw materials. Figure 2-4 shows the primary energy demand impacts of all foams. Results look very similar for other impact categories (acidification, eutrophication, etc.) except climate change indicated by global warming potential in Figure 2-5, which is shown to highlight the blowing agent effect on the embodied phases GWP. Figure 2-5 shows results based on the assumption that 50% of the total blowing agent (HFC-245fa used in medium-density and roofing foams) is emitted eventually with 10% emitted during installation, 24% emitted during lifetime in building, 16% emitted during end of life, and thus 50% remaining in product.

Because HFC-245fa has a GWP factor of 1030 kg CO_2-equivalent/kg (TRACI 2.0), the emissions of this blowing agent dominate the climate change results of the embodied phases. Based on research of foam insulation and HFC-245fa, assumptions of the emission rates varied from as little as 25% to as high as 75%. This study assumes an emission rate of 50%, which is in line with the value used in the PIMA study (Phelan et al., 2011). Because this value is an assumption, a sensitivity analysis was performed.

Figure 2-6 shows how the climate change results for embodied phases are affected by the emission rate of this blowing agent. As discussed in section 6.4, new generation blowing agents for ccSPF (medium-density and roofing foam) have been developed and are in the process of being commercialized. The GWP for some new generation blowing agents is reported to be over 100 times less than conventional blowing agents (Baasondorj, M., et.al, 2011). Referring to Figure 2-5 above, the climate change impact of medium-density and roofing foams using these new low-GWP blowing agents would similar to the low-density foams.

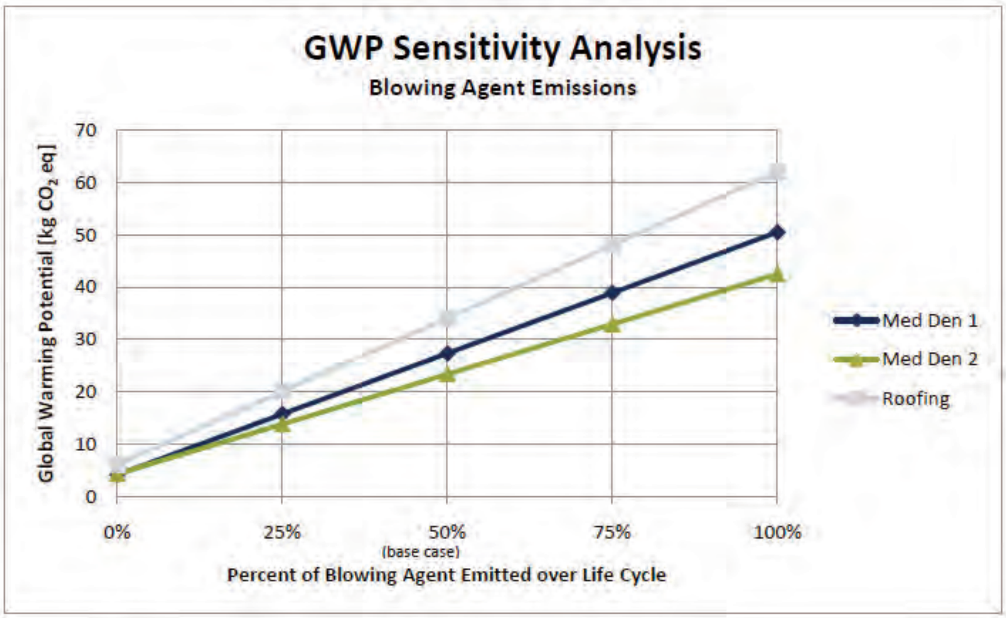


Figure 2-6 Sensitivity analysis of HFC-245fa blowing agent emissions, embodied life cycle phase (1 m^2, R_{SI}=1)

The embodied phases report (PE International Inc., 2012) provides similar details on the other impact categories (acidification, eutrophication, ozone depletion, and smog creation) as well as detailed breakdowns of the life cycle impact contributions of specific chemicals to the raw materials phase. As expected, the embodied life cycle impact contributions of the key raw material that makes up 50% of the spray foam by volume, pMDI, has the most significant effect on the raw material phase life cycle impacts. Also as expected, the other chemicals that make up a major part of the formulation after pMDI (i.e., polyols and flame retardant) follow pMDI in contributing most to the raw materials phase impacts.

It is important to recognize that the impacts contributed by the raw materials and other embodied phases are relatively insignificant when the entire life cycle (i.e., the use phase) is considered. As quantified in Section 5 of this report, the embodied phases contribute only a small fraction of the impacts compared to the more significant energy savings and GHG/other impacts avoided in the use phase.

Finally, it is recognized that that foam R-value and density may vary. Variation in the R-value and density of spray foam influences the environmental impacts. Installers report a range of R-values and densities achieved when spraying across different building types, regions of the country, and seasonal weather conditions. To determine the effect of this variability on the LCA results, a sensitivity analysis was performed on the primary energy demand to calculate the impacts based on the minimum and maximum observed R-values and densities. Also, the SPFA has compiled a range of published density and R-value information for spray foam from ICC-ES Evaluation Service Reports. The values used for calculating best and worst case scenarios come from that research (ASHRAE HOF, 2010). Table 2-8 shows the values used to calculate the results.

Table 2-8 Density and R-Values Used in Sensitivity Analysis

FOAM	PARAMETER	BEST CASE	STUDY RESULTS	WORST CASE
OPEN-CELL	Nominal Density	0.42	0.50	0.57
	Actual Density	0.73	0.86	0.99
	R-Value	4.2	3.6	3.2
CLOSED-CELL	Nominal Density	1.8	2.0	2.8
	Actual Density	2.81	3.12	4.37
	R-Value	7.0	6.2	5.8
ROOFING	Nominal Density	2.5	3.0	3.8
	Actual Density	4.36	4.58	5.24
	R-Value	7.1	6.2	5.9

Because the results are displayed for a functional unit with a set R-value, it is not surprising that increasing R-value of a foam product decreases the mass required and therefore its burden. The results also show that as the density increases, the impacts increase. Because of this, the highest burden scenario for each foam type occurs with maximum density values and minimum R-values, while the lowest burden scenarios are those with the minimum density and maximum R-value. As shown in Figure 2-7, the minimum impacts range from 85%-91% of the impacts found in the study. Conversely, the maximum impacts range from 114%-140% of the impacts found in the study. As the R-values and density affect all impacts equally, this sensitivity applies to all impacts. It is important to note that the best case and worst case scenarios are not equidistant from the study results. This non-uniformity is related to the observed range of density and R-value found in literature.

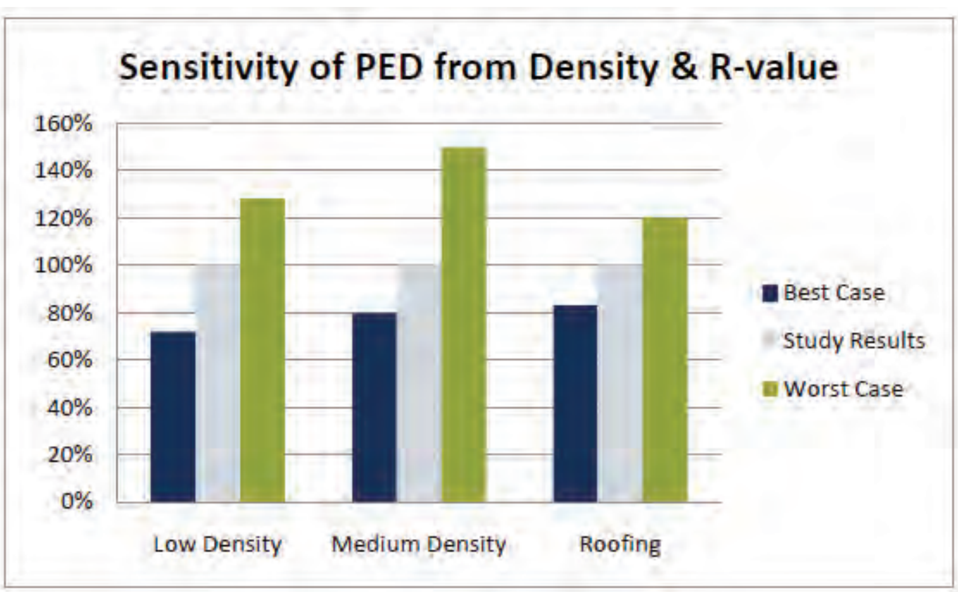


Figure 2-7 Sensitivity of PED from best to worst case density and R-values

3 SPF Applications

As described in Section 2.3, spray polyurethane foam is an insulation and roofing material that is formulated on the jobsite by the combination of pMDI, or “A-side,” with an equal volume of a polyol blend, or “B-side.” While the formulation of the A-side is essentially constant, the proprietary formulations of the B-side, which includes polyols, blowing agents, flame retardants, catalysts, and surfactants, will vary depending on the desired properties of the foam.

There are three basic classifications for spray polyurethane foam (SPF) used in the U.S. construction industry for insulation and roofing systems. These classifications are based on material density and cell structure. A summary of key physical properties of these foams is provided in Table 3- 1.

The first classification is open-cell or low-density SPF. This material has a core or nominal density ranging from 0.4 to 0.7 pounds per cubic foot (pcf), and often is referred to as “half-pound” or “water-blown” foam. These foams are formed using a reactive blowing agent, which is typically water. Water reacts with the A-side MDI to create CO_2 gas that expands the curing liquid into a cellular foam material. Because this material has an open cell structure, the cells are filled with air, so that the thermal performance (R-value per inch thickness or thermal resistivity) is in the range of R3.6 to R4.0 per inch. Open-cell SPF is permeable to moisture, and may need an additional vapor retarder in cold-climate building applications. However, open-cell SPF is air impermeable, and can serve as an air barrier material at certain thicknesses.

Figure 3-1 Installation of low-density SPF in a wood-framed wall

The second SPF class is closed-cell or medium-density SPF. This class of foam has a core or nominal density ranging from 1.7 to 2.3 pcf and is often called “two-pound” foam. This material has a cell structure where 90% or more of the cells are closed. When fluorocarbon (physical) blowing agents are used, the fluorocarbon liquid in the B-side converts to a gas from the heat of the reaction to expand the cells. Like a double-pane insulated window, this low thermal conductivity fluorocarbon gas helps yield a thermal resistivity between R5.8 to R6.8 per inch. Medium-density SPF is resistant to water absorption and effectively impermeable to moisture and air. In addition, medium-density foams have measureable stiffness and strength and can provide a moderate increase in the structural performance of certain building assemblies (NAHB Research Center, 1992 and 1996; Duncan et al., 2008).

The third class of SPF is roofing foam. Like medium-density foams, these materials have a closed-cell structure using the same captive fluorocarbon blowing agents as a medium-density SPF. The major difference between roofing SPF and medium-density SPF is the foam density. Roofing foams have nominal densities typically ranging from 2.5 up to 3.5 or, in some cases, 4.0 pcf and are often called "three-pound" SPF. This increased density provides a higher compressive strength needed to support foot traffic when installed on top surfaces of low slope roofs.

Figure 3-2 Installation of medium-density foam on the inside of a metal building

The three classes of SPF described above are applied by professionally-trained contractors to large areas of the building envelope using a two component, high-pressure delivery system. In recent years, there have been new foam formulations on the market having densities, closed-cell content, and thermal performance that fall in between the three traditional foam classifications described above. Because these foams are still being introduced into the market, this study is limited to the three traditional SPF classes described above.

Figure 3-3 Installation of roofing foam on a low-slope roof

Table 3-1 Summary of SPF Properties

	SPRAY FOAM CLASSIFICATION		
	LOW-DENSITY OR OCSPF	MEDIUM-DENSITY OR CCSPF	MED-DENSITY CLOSED-CELL
Nominal Density (pcf)	0.4 – 0.7	1.7 -2.3	2.5 – 3.5
Thermal Resistivity (R/in)	3.6 - 4.5	5.8 - 6.8	5.8 - 6.8
Air Impermeable Material	✓ (>4-6")	✓ (>1")	✓ (>1")
Integral Air Barrier System	✓	✓	✓
Class II Vapor Retarder		✓ (>2")	✓ (>2")
Water Resistant		✓	✓
Cavity Insulation	✓	✓	
Continuous Insulation	✓	✓	✓
Low-Slope Roofing			✓
Structural Improvement		✓	✓

3.1 SPF in Residential Housing

Medium-density SPF was introduced as insulation for residential buildings in response to demands for increased energy efficiency after the energy crises of the late 1970's and early 1980's. In the early 1990's, low-density SPF insulation entered the marketplace as a slightly less costly alternative to medium-density SPF. During the past five years, the use of SPF insulation has witnessed dramatic increases. From 2006 to 2008, the use of SPF insulation in the U.S. increased by 100% (Austin, 2011). From 2010 to 2011, usage increased by 8.4% (Austin, 2012). It is estimated that the total market share of SPF insulation has grown from 3% to 5% of residential buildings in the mid 2000's to about 10% to 15% of homes built in 2011.

SPF expands in place providing both insulation and an air barrier. This in-place expansion fills cracks, gaps, and penetrations in the building envelope. It can be used in the same envelope applications as fibrous insulations, and, due to its adhesive properties, it can be used in several additional locations unsuitable for fibrous insulations, such as under floors and below roof decks, to create more energy-efficient unvented attics.

Both low and medium-density SPF can be used interchangeably as an interior insulation and air-barrier system, however the thickness required will be different based on R-value requirements dictated by building and energy codes. For exterior application and below-grade assemblies, medium-density is preferred due to its water resistance and low moisture permeability.

In the use-phase analysis covered in Section 5 of this report, both low and medium-density SPF were considered interchangeable to provide interior insulation for walls, floors, and roofs of newly-constructed wood-frame homes in Houston, TX, Richmond, VA, and Minneapolis, MN. The thickness of the SPF insulation was varied to provide minimum R-values prescribed by the 2009 International Residential Code (IRC) (ICC, 2009).

3.2 SPF in Commercial Buildings

While low and medium-density SPF can be used as an interior insulation in commercial buildings and medium-density SPF exclusively on the exterior, the most common commercial building application for SPF is for new and replacement low-slope roof applications. Roofing SPF has been applied to low-slope roofs since the late 1960's. SPF can be used in new buildings or it can be directly applied over existing roof systems. SPF roofing is typically applied at a thickness of 1 to 2 inches and tapered to control drainage. After application, it is immediately covered with one of several polymeric coatings to protect it from UV light and surface abrasion.

There are several advantages to SPF roofing over other roofing systems. It provides a continuous insulation layer, eliminating the thermal 'shorts' created by gaps and fasteners used in other roof insulations. Its form-in-place and adhesive properties enable it to self-flash a wide range of roof penetrations and provide excellent wind uplift resistance.

In the use-phase analysis of this study, roofing-foam SPF was used to provide additional insulation to the exterior side of a low-slope roof on typical 1980's strip mall buildings in Houston, TX, Richmond, VA, and Minneapolis, MN. The thickness of the SPF insulation was used to increase the continuous R-value of the existing roof from R4 to both R12 and R20, to be compliant with the ASHRAE 90.1-2010 energy code.

4 Use Phase: Whole Building Energy Simulation

When new residential or commercial buildings are designed or when major energy efficiency improvements are made to existing buildings, engineers, building scientists, and energy analysts use software programs to predict the energy use of the completed building. There are many software programs recognized by the U.S. Department of Energy (U.S. DOE Software Tools) for this purpose. Most of these programs, when used by trained professionals, can predict energy use of new residential buildings within about 5% of actual use (Advanced Energy, 2009). These programs include effects of occupant use, lighting, appliances, hot water heating, and HVAC systems. They also incorporate the design of the building envelope, including the efficiency of windows and doors, and allow the analyst to prescribe different levels air leakage as well as the amount of insulation in the walls, floors, and roof areas. Local climate factors as well as building orientation and exposure are also included in these simulation programs.

4.1 Simulation Methods

For this study, two different energy simulation programs were employed. These simulations were conducted on typical buildings to evaluate the energy savings using SPF. For residential homes considered in this study, EnergyGauge software was used; for a typical type of commercial building (strip mall), U.S. DOE EnergyPlus software was used. All simulations were performed by Sustainable Solutions Corporation of Royersford, PA, under guidance of a registered professional engineer and independently evaluated by Steven Winter Associates of Norwalk, CT. The details of these simulations are summarized in separate reports (Sustainable Solutions Corporation, 2012).

4.2 Simulation Basis & Results

4.2.1 Residential

For this study, a typical (per NAHB Research Center Survey) 2,434 square-foot two-story wood-framed home, as shown in Figure 4-1, was modeled using the EnergyGauge program. With the exception of insulation and air infiltration levels, all other aspects of the home remained unchanged.

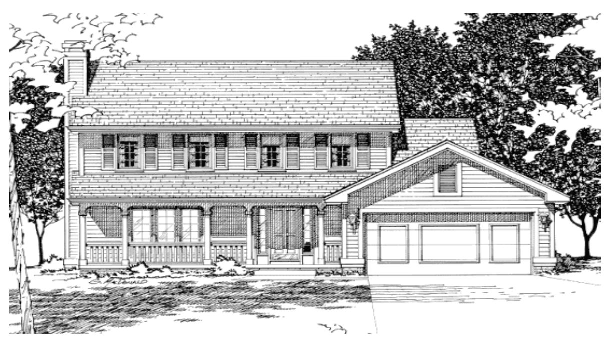


Figure 4-1 Typical residential home used in energy model

The residential energy modeling documented in the energy simulation reports (Sustainable Solutions Corporation, 2012) compared the use phase of a SPF insulated home to two baselines: zero insulation and conventional fibrous insulation. However, because comparable embodied phase life cycle results for fibrous insulation are not available, an evaluation of the entire life cycle (embodied and use phases) for conventional insulation was not conducted. Therefore, this report shows results for a baseline home with no cavity insulation versus spray foam insulation. Air infiltration rates for the baseline home and those with spray foam insulation are given in Table 4-1. For spray foam insulation, two cases were modeled. Case 1 and Case 2 used SPF insulation to provide the same R-value as conventionally insulated homes, but the infiltration rate was lowered to 0.1 ACH_n based on average infiltration rates measured for homes using SPF (Chan et al., “Air Infiltration Data Analysis for Newly Constructed Homes Insulated with Icynene Spray Foam,” 2003). As described in Table 4-1, Case 1 applied insulation to the attic floor while Case 2 applied insulation under the roof deck to create an unvented attic. Case 1 was assumed for all three climates whereas Case 2 was only modeled for the Houston climate (IECC Zone 2A).

The building energy simulations for the homes were completed using RESNET-approved EnergyGauge software. Minimum prescriptive R-values are used for spray foam insulation per the 2009 IRC, Chapter 11 for each location (ICC, 2009). The effect of SPF versus no insulation is the R-value combined with significantly reduced air infiltration due to the air sealing properties of spray foam. Although the comparison is not shown for reasons noted, if SPF were compared to conventional air permeable insulation, the air sealing and infiltration rates of SPF would be superior as SPF will allow less infiltration compared to conventional insulation.

When comparing SPF to no insulation, there will be a significant increase in R-value for the wall and ceiling assemblies as well as the same improvement regarding infiltration rate. SSC evaluated multiple studies and data sources to identify an accurate infiltration rate for conventionally insulated new homes and spray foam insulated new homes. Much of the data was based on blower door testing of existing and new homes, which provides "real world data" based on actual homes.

The model home for each climate zone is typical construction for the home size and type based on NAHB Builders' Practices Survey and the prescriptive requirements of the 2009 IECC Energy Code. This approach provides a better understanding of the typical energy usage in each region. Extracts of the residential modeling input and results follow below. The key results are provided in Table 4-2.

Table 4-1 Descriptions of Residential Energy Modeling Cases

CASE	DESCRIPTION
Baseline	Typical new home construction, no added insulation, using maximum climate-zone dependent infiltration rate from IECC 2009 Section N1102.4.2.1 (0.43, 0.33, or 0.32 ACH_n)
Case 1	Spray foam insulation with whole house ventilation, insulation applied to attic floor, using infiltration rate from NAHB study (0.1 ACH_n). Some exposed HVAC ductwork in vented attic.
Case 2	Spray foam insulation with whole house ventilation, insulation applied to underside of roof deck and over roof rafters to create unvented attic enclosing entire HVAC system inside building envelope, using infiltration rate from NAHB study (0.1 ACH_n)

Table 4-2 Key Results from the Residential Energy Modeling

	HOUSTON (IECC ZONE 2A)		
	NO INSULATION	SPRAY FOAM	
CASE	BASELINE	CASE 1	CASE 2
Attic Floor Insulation Thermal Resistivity	R0	R30	
Roof Deck Insulation			R30
Wall Construction	2x4 16"oc	2x4 16"oc	2x4 16 oc
Wall Insulation (cavity) Thermal Resistivity	R0	R13	R13
Ventilation	Exhaust	ERV (78% 55 cfm)	ERV (78% 67 cfm)
Air Infiltration (ACHn)	0.32	0.1	0.1
HERS Score	129	88	75
Annual Cooling (kWh)	7087	4781	3489
Annual Heating (kWh)	2667	934	782
Annual Heating (therms)	0	0	0

	RICHMOND (IECC ZONE 4A)	
	NO INSULATION	SPRAY FOAM
CASE	BASELINE	CASE 1
Attic Floor Insulation Thermal Resistivity	R0	R38
Wall Construction	2x4 16" oc	2x4 16" oc
Wall Insulation (cavity) Thermal Resistivity	R0	R13
Ventilation	Exhaust	ERV (78% 67 cfm)
Air Infiltration (ACHn)	0.33	0.1
HERS Score	122	70
Annual Cooling (kWh)	3665	2439
Annual Heating (kWh)	778	482
Annual Heating (therms)	994	244

	MINNEAPOLIS (IECC ZONE 6A)	
	NO INSULATION	SPRAY FOAM
CASE	BASELINE	CASE 1
Attic Floor Insulation Thermal Resistivity	R0	R49
Wall Construction	2x4 16" oc	2x4 16" oc
Wall Insulation (cavity) Thermal Resistivity	R0	R19
Ventilation	Exhaust	ERV (78% 67 cfm)
Air Infiltration (ACHn)	0.43	0.1
HERS Score	138	66
Annual Cooling (kWh)	1933	1062
Annual Heating (kWh)	1732	807
Annual Heating (therms)	2217	579

4.2.2 Commercial

For this study, a typical 1980's vintage 22,500 square-foot strip mall (U.S. DOE Reference Building) as shown in Figure 4-2 was modeled using the EnergyPlus program.

The commercial energy modeling compared the building using two baselines: existing R4 roof deck insulation (R4 baseline) and existing R12 roof deck insulation (R12 baseline). It is assumed that these baseline roof deck insulation levels are typical for this 30-year old building. A SPF roofing system was applied to increase the total roof deck insulation to R20, as required by the ASHRAE 90.1-2010. Because little data exist for air leakage using different roofing systems, the air infiltration values used in the analysis were held constant for all cases. All other aspects of the building, with the exception of roof deck insulation levels, were held constant. Key results are provided in Table 4-3.

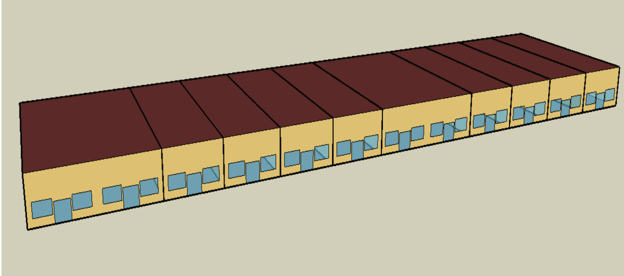


Figure 4-2 Typical 22,500 ft^2 strip mall

Table 4-3 Key Results from Commercial Building Energy Analysis

	HOUSTON (IECC ZONE 2A)		
	EXISTING BOARDSTOCK ROOF INSULATION	EXISTING BOARDSTOCK ROOF INSULATION	EXISTING BOARDSTOCK PLUS SPF ROOF INSULATION
CASE	R4 BASELINE	R12 BASELINE	R20 with added SPF
Roof Deck Insulation Thermal Resistivity	R4	R12	R20
Ventilation Fans (kWh)	107,600	83,100	74,100
Space Cooling (kWh)	155,400	129,800	120,700
Annual Heating (therms)	2900	2500	2300

	RICHMOND (IECC ZONE 4A)		
	EXISTING BOARDSTOCK ROOF INSULATION	EXISTING BOARDSTOCK ROOF INSULATION	EXISTING BOARDSTOCK PLUS SPF ROOF INSULATION
CASE	R4 BASELINE	R12 BASELINE	R20 with added SPF
Roof Deck Insulation Thermal Resistivity	R4	R12	R20
Ventilation Fans (kWh)	97,300	75,000	67,300
Space Cooling (kWh)	81,000	64,300	58,000
Annual Heating (therms)	9800	8400	8000

	MINNEAPOLIS (IECC ZONE 6A)		
	EXISTING BOARDSTOCK ROOF INSULATION	EXISTING BOARDSTOCK ROOF INSULATION	EXISTING BOARDSTOCK PLUS SPF ROOF INSULATION
CASE	R4 BASELINE	R12 BASELINE	R20 with added SPF
Roof Deck Insulation Thermal Resistivity	R4	R12	R20
Ventilation Fans (kWh)	114,800	96,900	92,700
Space Cooling (kWh)	43,200	34,500	31,200
Annual Heating (therms)	23,000	20,000	19,100

5 The Complete Life Cycle Picture – Results

5.1 The SPF Insulation Life Cycle

The entire spray foam insulation life cycle consists of cradle-to-end of life phases for making, processing, transporting, installing, using, and, finally, disposing of spray foam insulation. For purposes of analysis, the spray foam insulation life cycle was divided into the following five key phases:

1. Raw Materials Manufacturing and Blending

2. Transportation

3. Installation

4. Use Phase

5. End of Life

The results in Section 2 focus on the embodied phases of a product (i.e., energy and environmental impacts associated with phases 1, 2, 3, and 5). Regarding phase 4, section 2 covers only environmental impacts associated with blowing agent emitted during the use phase. Standard life cycle inventory and impact assessment methodology described in ISO LCA standards (ISO 14040: 2006; ISO 14044: 2006) are used for estimating these environmental impacts.

As in any comprehensive life cycle assessment, the embodied phases and their associated impacts do not tell the whole story because the energy saved and environmental impacts avoided during insulation use must be considered. Determining energy savings and environmental impacts avoided during insulation use requires a different methodology not covered in ISO 14040/ISO 14044, sometimes called whole building energy simulation/modeling or analysis. The whole building energy modeling uses the simulation tools described in Section 4 of this report. Combining energy and environmental impacts generated in the embodied phases (Section 2) with the energy and environmental impacts reduced during spray foam insulation use (Section 4) provides a complete picture of the spray foam insulation life cycle.

5.2 Life Cycle Impacts and Scenarios

The following sections focus on the total SPF insulation life cycle for each of the following environmental impact categories:

- Primary energy from (non-renewable) resources
- Climate change
- Acidification
- Eutrophication
- Ozone depletion
- Smog creation

The impact categories listed above are assessed quantitatively using the associated characterization factors listed in Table 5-1 below.

Typical applications used to demonstrate life cycle results for each of the above six categories in Climate Zones 2, 4, and 6 include:

- New residential housing (low-density and medium-density foams) in walls and roof/ceiling
- Commercial building roof retrofit with medium-density roofing foam

Because the service life for spray foam insulation as defined in the LCA is 60 years, this period is used to illustrate the benefits for both residential and commercial applications. The 60-year service life is also consistent with the functional unit for insulation defined in the Product Category Rule (PCR) for building envelope thermal insulation (UL Environment, 2011).

Regarding new residential housing applications, results for embodied phase impacts (energy resources, greenhouse gas emissions generated, acidification generated, etc.) are combined with the use phase (energy saved, greenhouse gas emissions avoided, acidification avoided, etc.) for residential houses in Climate Zone 2 (Houston), Zone 4 (Richmond), and Zone 6 (Minneapolis). A house with a baseline case of no cavity insulation versus SPF insulation per code is used to demonstrate the value of SPF insulation on a new house. Although energy simulation modeling (Sustainable Solutions Corporation, 2012) was performed for SPF and conventional air-permeable insulation, these results are not discussed in this report. This is because comparable embodied values of the fibrous insulation are not available and it is not technically correct to compare the entire insulation life cycle of materials using values developed under different methodologies.

The comparisons for a commercial building (U.S. DOE representative strip mall) roofing retrofit located in Climate Zone 2 (Houston), Zone 4 (Richmond), and Zone 6 (Minneapolis) include a strip mall roof with a base case of R4 roof insulation versus additional SPF roof insulation to bring the total to R20, and a base case of R12 roof insulation versus additional SPF roof insulation to bring the total to R20.

5.3 Life Cycle Impact Category Factors

The factors in Table 5-1 below are used to calculate the energy savings and environmental impacts avoided during the spray foam insulation use phase for residential and commercial scenarios studied. The savings in electricity and natural gas determined from the energy simulation modeling are multiplied by these values to provide the use phase impact reductions for each impact category. The denominator of each unit refers to MJ of energy delivered or metered at the site. Because the embodied life cycle energy and environmental impacts are calculated using U.S. average factors for electricity and natural gas, the energy savings and environmental impacts avoided in the use phase are estimated using the same impact category factors for consistency.

Table 5-1 Life Cycle Impact Category Characterization Factors for Use Phase Calculations

LIFE CYCLE IMPACT CATEGORY CHARACTERIZATION FACTOR[4]	UNITS	ELECTRICITY (U.S. AVERAGE)[1]	NATURAL GAS (U.S. AVERAGE)[2]	FACTOR RATIO (ELECTRICITY / NATURAL GAS)
Primary Energy from Resources, LHV	[MJ/MJ]	2.68	1.26	2.1
Global Warming Potential (GWP)	[kg CO_2-Equiv./MJ]	0.185	0.0761	2.4
Acidification Potential (AP)	[H+ moles-Equiv./MJ]	0.0442	0.00451	9.8
Eutrophication Potential (EP)	[kg N-Equiv./MJ]	1.81E-05	4.02E-06	4.5
Ozone Depletion Potential (ODP)[3]	[kg CFC 11-Equiv./MJ]	1.91E-09	2.11E-10	9.1
Smog Creation Potential (SCP)	[kg O_3-Equiv./MJ]	0.00706	0.00181	3.9

1. U.S.: Electricity grid mix, GaBi5 Database, PE Intl., Ref. year: 2008 / Valid until: 2013
2. U.S.: Thermal Energy from Natural Gas, GaBi5 Database, PE Intl., Ref. year: 2008 / Valid until: 2013
3. ODP values corrected per TRACI 2.0 database (U.S. EPA)
4. All categories except Primary Energy based on TRACI 2.0 Impact Assessment Methodology (U.S. EPA)

For example, the metered (or site) energy saved during the use phase is multiplied by source energy factors for electricity generation and natural gas in Table 5-1 as this adjustment considers the life cycle energy needed for generating electricity and natural gas including extraction of coal, uranium, crude oil, and natural gas, efficiency of conversion, distribution losses, etc. This adjustment also makes the energy savings comparable with the embodied energy, which is also done on a life cycle basis. The source energy factor used for electric power is the U.S. national average of 2.68, meaning that it requires over two and a half times the MJ to deliver 1 MJ of energy metered at the building site. Similarly, the source energy factor used for natural gas is 1.26, meaning that it requires 1.26 MJ to deliver 1 MJ of natural gas to the building site. GHGs and impacts for other categories avoided in the use phase also are calculated based on the metered (or site) energy estimated by the energy simulation modeling for the scenarios noted. Thus, GWP, AP, EP, etc., avoided in the use phase are based on the metered (or site) energy multiplied by the corresponding characterization factors so that all calculations include life cycle impacts associated with generating electricity and natural gas.

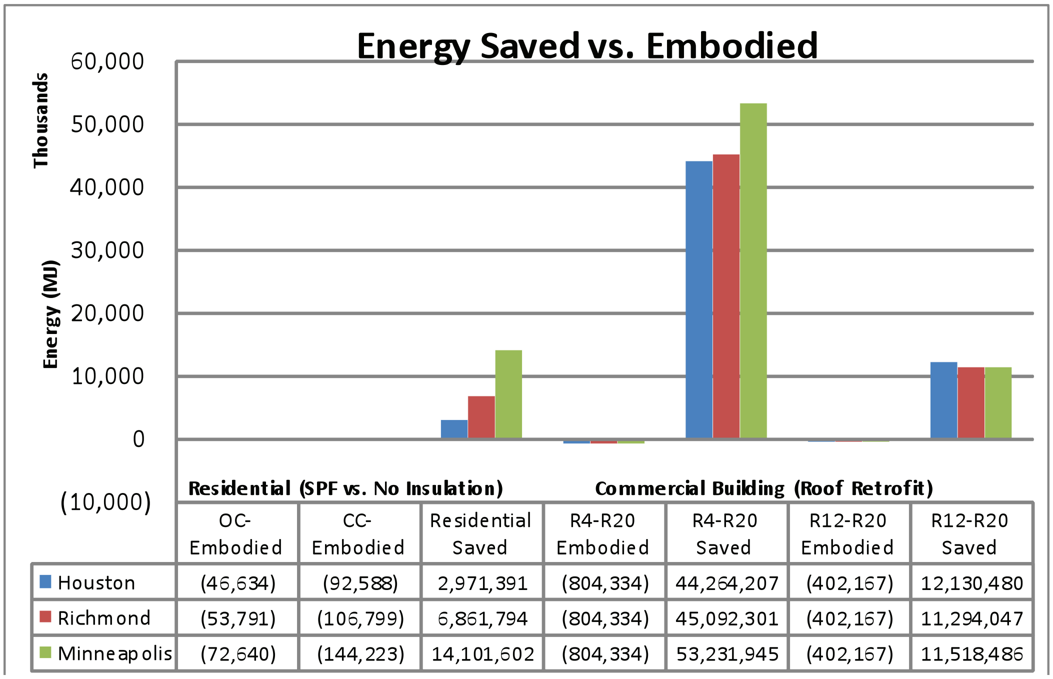
The above characterization factor ratios in Table 5-1 for electricity and natural gas demonstrate the degree to which natural gas has less environmental impacts per MJ delivered than electricity. For example, the AP factor associated with natural gas is almost 10 times less compared to the AP factor for electric power as emissions of SOx, NOx etc., associated with electric power generation are much greater than those for natural gas.

5.4 Life Cycle Impacts of SPF Insulation on Residential Houses and Commercial Buildings

Figures 5-1 through 5-6 below show the total life cycle impacts by each of the six impact categories for a new residential house with open-cell (low-density) and closed-cell (medium-density) SPF insulation compared to no cavity insulation. Also shown for each impact category are results for a commercial building roof insulation retrofit, where SPF is added to existing R4 and R12 baseline insulation levels to bring the total to R20.

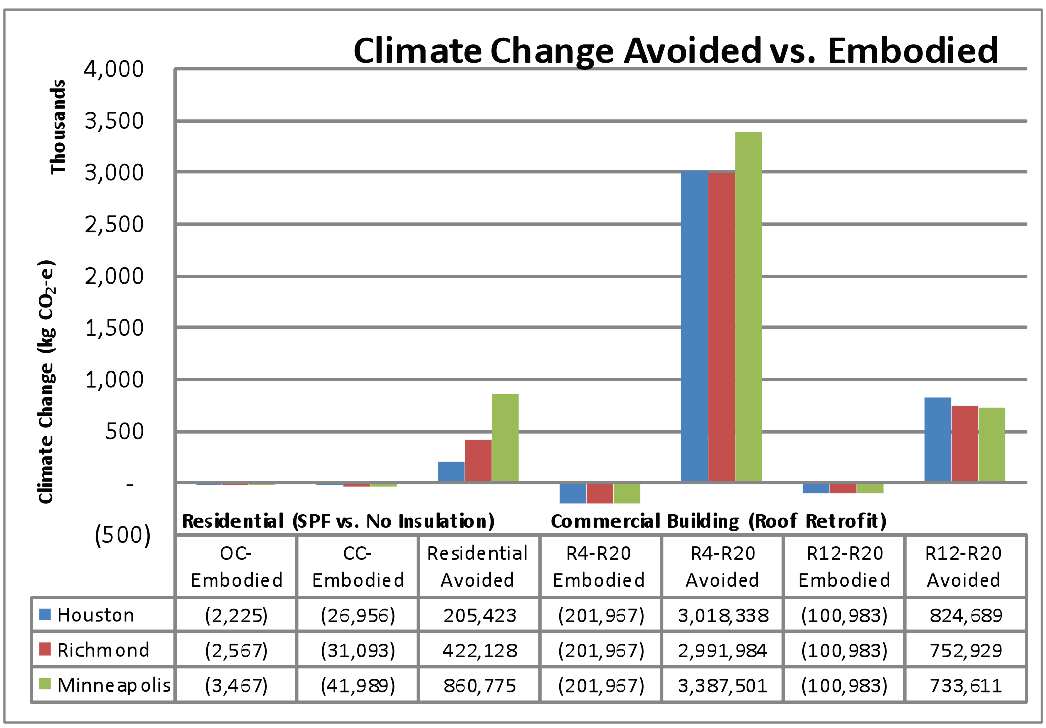
The magnitude of energy savings, GHGs, and other environmental impacts avoided for the commercial building roof retrofit is significantly greater than that for the residential housing. The primary reason causing this significant difference in the magnitude of energy savings results from a commercial roof insulated area that is approximately 10 times greater than the insulated area of the residential house modeled.

In the case of all impact categories, the embodied energy and environmental impacts are minimal when compared to the much greater energy savings and environmental impacts avoided during insulation use for 60 years.



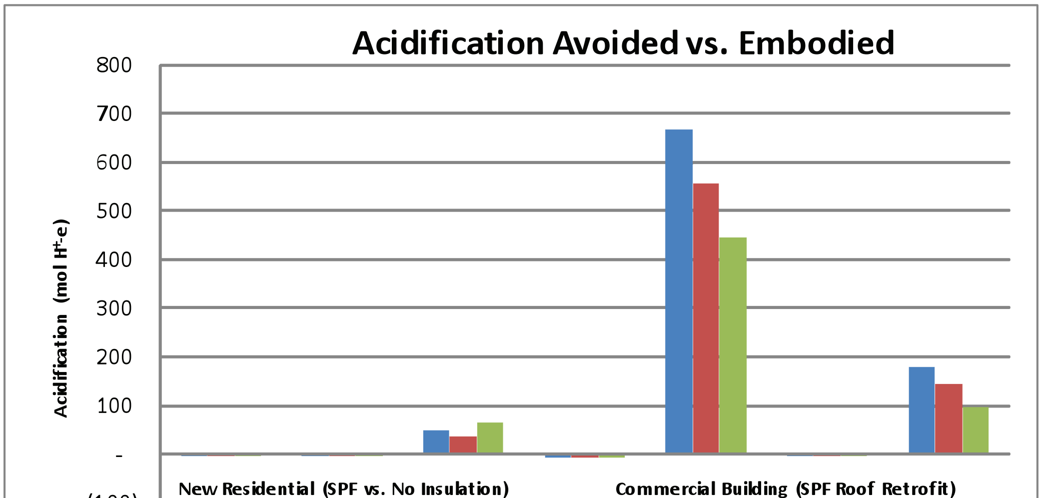
	OC-Embodied	CC-Embodied	Residential Saved	R4-R20 Embodied	R4-R20 Saved	R12-R20 Embodied	R12-R20 Saved
Houston	(46,634)	(92,588)	2,971,391	(804,334)	44,264,207	(402,167)	12,130,480
Richmond	(53,791)	(106,799)	6,861,794	(804,334)	45,092,301	(402,167)	11,294,047
Minneapolis	(72,640)	(144,223)	14,101,602	(804,334)	53,231,945	(402,167)	11,518,486

Figure 5-1 Life cycle primary energy from resources (MJ), 2,464 ft² residential house / 22,500 ft² strip mall roof, 60 years



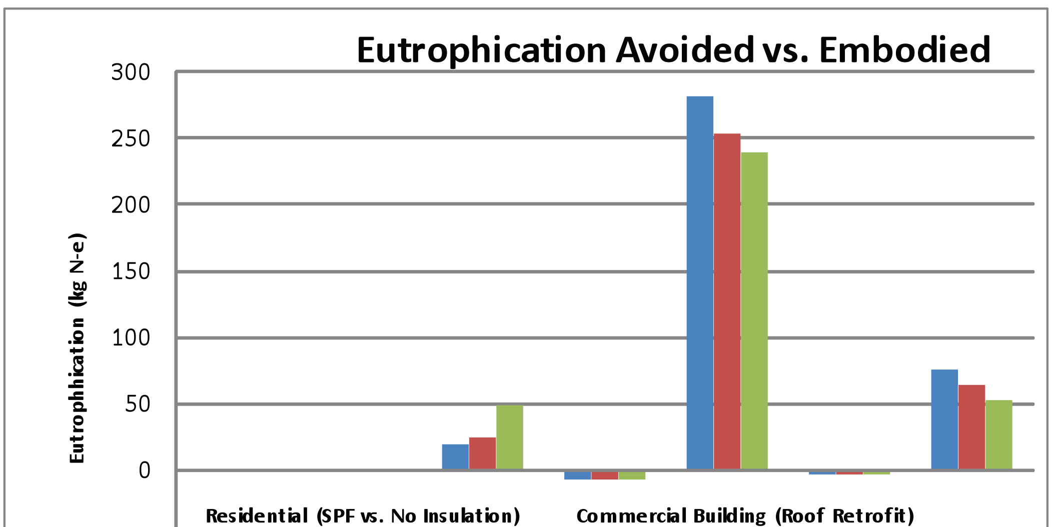
	OC-Embodied	CC-Embodied	Residential Avoided	R4-R20 Embodied	R4-R20 Avoided	R12-R20 Embodied	R12-R20 Avoided
Houston	(2,225)	(26,956)	205,423	(201,967)	3,018,338	(100,983)	824,689
Richmond	(2,567)	(31,093)	422,128	(201,967)	2,991,984	(100,983)	752,929
Minneapolis	(3,467)	(41,989)	860,775	(201,967)	3,387,501	(100,983)	733,611

Figure 5-2 Life cycle greenhouse gas emissions (kg CO_2-equivalent), 2,464 ft² residential house / 22,500 ft² strip mall roof, 60 years



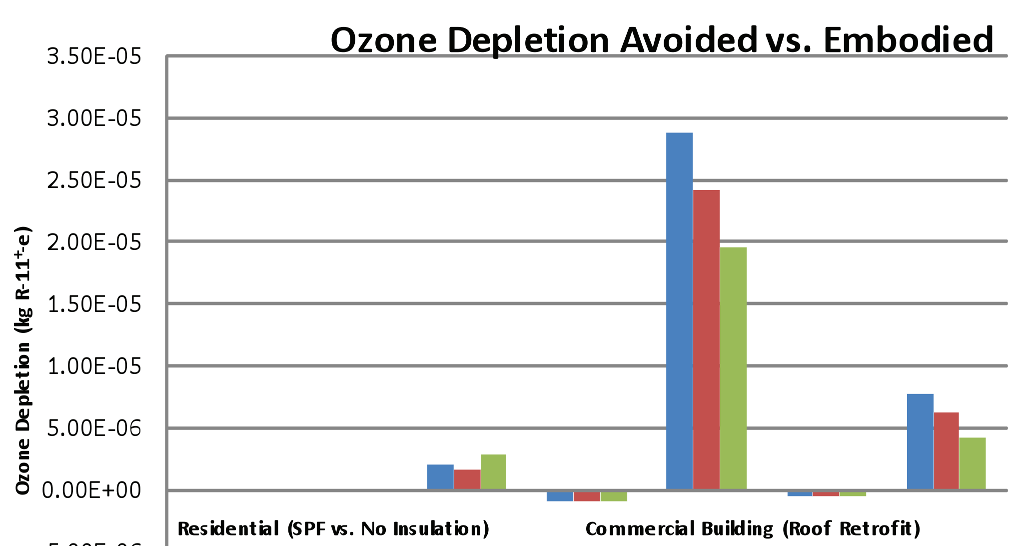
	OC-Embodied	CC-Embodied	Residential Avoided	R4-R20 Embodied	R4-R20 Avoided	R12-R20 Embodied	R12-R20 Avoided
Houston	(366)	(761)	48,969	(6,306)	667,754	(3,153)	179,337
Richmond	(422)	(878)	35,927	(6,306)	557,951	(3,153)	144,977
Minneapolis	(570)	(1,185)	63,887	(6,306)	445,195	(3,153)	97,239

Figure 5-3 Life cycle acidification (moles H+-equivalent), 2,464 ft² residential house / 22,500 ft² strip mall roof, 60 years



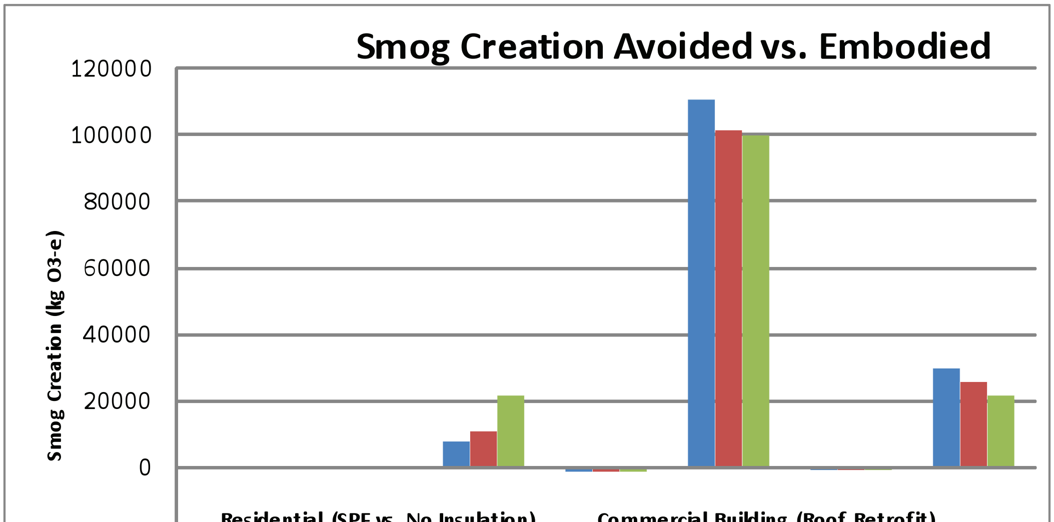
	OC-Embodied	CC-Embodied	Residential Avoided	R4-R20 Embodied	R4-R20 Avoided	R12-R20 Embodied	R12-R20 Avoided
Houston	(0.40)	(0.88)	20.05	(7.83)	282	(3.92)	76
Richmond	(0.46)	(1.01)	25.03	(7.83)	253	(3.92)	65
Minneapolis	(0.62)	(1.37)	48.69	(7.83)	240	(3.92)	52

Figure 5-4 Life cycle eutrophication (kg N-equivalent), 2,464 ft² residential house / 22,500 ft² strip mall roof, 60 years



	OC-Embodied	CC-Embodied	Residential Avoided	R4-R20 Embodied	R4-R20 Avoided	R12-R20 Embodied	R12-R20 Avoided
Houston	-4.76E-05	-1.08E-04	2.11E-03	-9.71E-04	2.89E-02	-4.85E-04	7.76E-03
Richmond	-5.49E-05	-1.24E-04	1.63E-03	-9.71E-04	2.43E-02	-4.85E-04	6.30E-03
Minneapolis	-7.41E-05	-1.68E-04	2.93E-03	-9.71E-04	1.96E-02	-4.85E-04	4.29E-03

Figure 5-5 Life cycle ozone depletion (kg CFC11-equivalent), 2,464 ft² residential house / 22,500 ft² strip mall roof, 60 years



	OC-Embodied	CC-Embodied	Residential Avoided	R4-R20 Embodied	R4-R20 Avoided	R12-R20 Embodied	R12-R20 Avoided
Houston	(87)	(175)	7,823	(1,566)	110,810	(783)	30,028
Richmond	(100)	(202)	10,911	(1,566)	101,544	(783)	25,918
Minneapolis	(135)	(272)	21,501	(1,566)	100,080	(783)	21,740

Figure 5-6 Life cycle smog creation (kg O3-equivalent), 2,464 ft² residential house / 22,500 ft² strip mall roof, 60 years

5.5 Life Cycle Payback Analysis

Table 5-2 below shows the energy saved/embodied and GHG avoided/embodied ratios and payback periods in detail for both the residential and commercial scenarios as energy with its cost implications and climate change are typically of interest to many stakeholders.

As seen in Table 5-2, when the ratio of energy saved or GHG avoided is higher, the payback is shorter. In fact, there is a direct correlation. Because the use phase savings or GHG avoided are for a 60-year period, the ratio is the reciprocal of the payback period times 60. For example, in Richmond, the ocSPF Saved/Embodied Energy is 127.6 and the reciprocal or ocSPF embodied/saved ratio is 0.0078, which also shows the negligible embodied energy compared to the savings. Multiplying by 60 years yields the payback of 0.5 shown in the table.

Table 5-2 Energy and GHG Payback Analysis, 2,464 ft^2 Residential House / 22,500 ft^2 Strip Mall Roof, 60 Years

BUILDING TYPE	RATIO and PAYBACK	HOUSTON		RICHMOND		MINNEAPOLIS	
		ENERGY	GHG	ENERGY	GHG	ENERGY	GHG
Residential Insulation	ocSPF-Saved/Embodied	63.7	92.3	127.6	164.4	194.1	248.3
	ocSPF-Payback (Yr)	0.9	0.7	0.5	0.4	0.3	0.2
	ccSPF-Saved/Embodied	32.1	7.6	64.2	13.6	97.8	20.5
	ccSPF-Payback (Yr)	1.9	7.9	0.9	4.4	0.6	2.9
Commercial Roofing	R4-R20 Avoided/Embodied	55.0	14.9	56.1	14.8	66.2	16.8
	R4-R20 Payback (Yr)	1.1	4.0	1.1	4.1	0.9	3.6
	R12-R20 Avoided/Embodied	30.2	8.2	28.1	7.5	28.6	7.3
	R12-R20 Payback (Yr)	2.0	7.3	2.1	8.0	2.1	8.3

Regarding the residential energy paybacks shown in Table 5-2 above, Houston clearly has longer energy payback periods even though Houston has the lowest embodied energy. The higher embodied energy in the other zones results from higher volumes of insulation required, thus 1.3 and 1.6 times the volume of insulation is required in Richmond and Minneapolis, respectively, compared to Houston. However, the energy savings achieved by SPF insulation in the Richmond and Minneapolis houses is 2.3 to 4.8 times greater than the energy savings in Houston. This is expected because heating energy saved in Richmond/Minneapolis far overwhelms the cooling energy saved in Houston by installing SPF to required code.

Also, the much higher ratios of saved/embodied energy (2 to 3 times higher in Richmond and Minneapolis versus Houston) is an indication of just how much more energy is saved by insulation in the temperate/cooler climate zones. As expected, ccSPF insulation has energy paybacks which are about twice as high versus ocSPF insulation as the embodied energy for ccSPF insulation is about twice as high compared to ocSPF insulation. The higher embodied energy for ccSPF versus ocSPF results from a ccSPF density that is 3.5 times greater than ocSPF, even though ocSPF requires 1.7 times the insulation volume compared to ccSPF insulation.

Regarding the residential GHG paybacks shown in Table 5-2 above, Houston again clearly has longer payback periods and the trends follow those discussed above for energy payback. The trends for energy savings and GHG avoided are similar because the ratios of electricity/natural gas characterization factors shown in Table 5-2 are similar: for Primary Energy from Resources the ratio is 2.1, and for GWP the ratio is 2.4. The results for GHG, however, highlight the impact of the blowing agent used in ccSPF (GWP approximately 1,000) versus the water used as the blowing agent in ocSPF (negligible GWP). As a result, the GHG payback periods for ccSPF are in the range of approximately 10 to 15 times greater for ccSPF compared to ocSPF insulation. Despite the much GWP higher blowing agent used in ccSPF insulation, the GHG payback periods for ccSPF insulation are still reasonable, ranging from under eight years in Houston to under three years in Minneapolis.

When it comes to the amounts of insulation on a commercial roofing retrofit, the embodied energy and GHGs of the ccSPF in going from R4 to R20 (additional R16) are twice that of the R12 to R20 (additional R8) case. However, the energy saved and GHG avoided with twice the amount of insulation are about 3.5 to 4.5 greater. As expected, there are diminishing returns when more insulation is added as retrofitting from R4 to R12 achieves 70% to 80% of the total energy savings of an R4 to R20 retrofit. However, the magnitude of additional energy savings achieved from R12 to R20 are still quite significant as seen in Figure 5-1: 11 to 12 million MJ (10.4 to 11.4 billion Btu).

In general, the additional R8 and R16 scenarios across climate zones show similar energy and GHG paybacks for all cities, indicating that installing both amounts of ccSPF on a commercial roof yield similar benefits in all zones. As expected due to heating energy, installing ccSPF on the roof results in energy savings and GHG avoided that is increasingly greater going from Houston to Minneapolis. For example, when an additional R16 is installed, this results in an energy savings/embodied ratio of 66.2 and an avoided GHG/embodied ratio of 16.8 in Minneapolis. There is a much greater amount of natural gas heating energy saved for the commercial building in Minneapolis, where 2.4 to 7 times the natural gas energy is required compared to Richmond and Houston, respectively. Thus, energy savings and GHG avoided increase more in the colder climate zones, but the benefits are still significant in all zones.

Table 5-3 below shows the avoided/embodied ratios and payback periods for the other impact categories, where the minimum and maximum values within the other four categories combined are given.

Table 5-3 Other Impact Categories* Payback Analysis, 2,464 ft^2 Residential House / 22,500 ft^2 Strip Mall Roof, 60 Years

BUILDING TYPE	RATIO and PAYBACK	HOUSTON	RICHMOND	MINNEAPOLIS
Residential Insulation	ocSPF-Saved/Embodied	(34.7~133.9)	(23.2~109)	(30.9~159)
	ocSPF-Payback (Yr)	(0.4~1.7)	(0.6~2.6)	(0.4~1.9)
	ccSPF-Saved/Embodied	(18.8~64.4)	(12.6~54.1)	(16.7~79)
	ccSPF-Payback (Yr)	(0.9~3.2)	(1.1~4.8)	(0.8~3.6)
Commercial Roofing	R4-R20 Avoided/Embodied	(29.4~105.9)	(24.7~88.5)	(20~70.6)
	R4-R20 Payback (Yr)	(0.6~2.0)	(0.7~2.4)	(0.8~3.0)
	R12-R20 Avoided/Embodied	(15.8~56.9)	(12.8~46)	(8.7~30.8)
	R12-R20 Payback (Yr)	(1.1~3.8)	(1.3~4.7)	(1.9~6.9)

*Other impact categories include acidification, eutrophication, ozone depletion, and smog creation. Detailed tables can be found in Appendix A.

As shown in Table 5-3 above for residential applications, ccSPF has a longer payback time than ocSPF among all three cities as the embodied impacts for ccSPF are generally about two times greater than those for ocSPF as a result of ccSPF insulation's higher density despite the greater volume of ocSPF insulation required. Correspondingly, the payback period for ccSPF insulation is about twice as long versus ocSPF. Geographically, Houston generally has a shorter payback time for both ocSPF and ccSPF than Minneapolis and Richmond in residential applications as the embodied aspects for Houston are the lowest (because less insulation is required) and Houston uses the most electricity versus the other zones. Because the other impacts' characterization factors for electricity are 4 to 10 times greater than those for natural gas, the impacts avoided in Houston for saving electricity have a dominant effect in reducing the payback times for that climate zone. Compared to Houston, electricity saved in Richmond is about a third even though more natural gas is used. However, because electricity has more intensive impacts versus natural gas per MJ energy saved in these four categories, lower amounts of electricity saved leads to a longer payback period in Richmond. Thus, the environmental impacts reduced by using insulation depend significantly on the type of energy used.

Similarly, for commercial roofing applications, Houston has the shortest payback times because electricity use is greater in Houston versus the other two zones and the impacts avoided by saving electricity are greater than those for natural gas, as discussed above. However, instead of Richmond as seen in residential applications, Minneapolis has the longest payback time in commercial roofing applications. The relative amount of electricity used in the Minneapolis building is lower than the other zones, and thus there are lower impacts avoided from relatively lower electricity use, resulting in longer payback times. Again, just as shown in the residential scenarios, the proportion of electricity and natural gas use combined with the higher impact characterization factors for electricity has a significant effect on environmental impact reduction.

Also, within commercial roofing applications, increasing insulation from R4 to R20 has a shorter payback time (approximately half as much) than increasing from R12 to R20. Despite twice as much embodied impact for thicker insulation needed for the R4 to R20 case and diminishing returns of more insulation, the amount of impacts avoided by reducing energy in the use phase plays the greatest role. Again, use phase performance of spray foam insulation has the greatest impact on environmental impact reduction, with the embodied phase being a relatively minor contributor to the life cycle impacts.

6 Observations and Conclusions

6.1 Use Phase Dominates Energy and Environmental Performance: Embodied Phase Contribution is Minimal

Although reductions in life cycle impacts vary by class of SPF, building type, climate zone/code requirements, type of building operating energy used, etc., the use phase is by far the largest life cycle contributor for all impacts studied. Embodied impacts are a fraction (generally several percent) compared to impacts reduced in the use phase and the payback periods are relatively short, typically ranging from several months to several years. Embodied impacts from transportation, for example, are even more negligible as transportation typically accounts for only 2% to 5% of the total embodied phases for most impact categories. Thus, from an environmental improvement perspective, it makes sense to promote and further expand the use of SPF insulation based on its performance, which results from superior thermal resistance and air sealing capabilities. Reducing impacts in the embodied phases may be desirable from a theoretical viewpoint, but it will have minimal environmental impact compared to benefits of using SPF in residential housing and commercial buildings.

6.2 Type of Energy for Operating Buildings has a Major Impact on Environmental Impacts Avoided in the Use Phase

Based on the U.S. average electric power mix and thermal energy from natural gas, life cycle impacts from electricity use are noticeably greater (from several to nearly 10 times) than those associated with natural gas. Thus, insulation will achieve relatively greater energy and environmental impact reductions in buildings using primarily electricity versus natural gas.

6.3 There are Increasing Energy Savings and GHG Avoided from Climate Zone 2 (Houston) to Climate Zones 4 (Richmond) and 6 (Minneapolis)

Although energy saved and GHGs avoided are impressive in all climate zones studied, energy and GHG benefits are greater in the more temperate climate zones. This is expected due to outside versus inside temperature differences (more heating degree days) in the colder, more temperate zones. In fact, air infiltration limits are more stringent in building codes governing colder climates as a result of such temperature differences. Thus, spray foam insulation with its high thermal resistivity and sealing properties always pays off no matter where a building is located, but it generally has greater energy and associated GHG benefits in colder climate zones.

6.4 Opportunities for Further Reducing Environmental Impacts with the SPF Life Cycle

6.4.1 Primary Energy from Resources

Regarding embodied phases, across all types of foam raw materials make up about 90% of the energy use in the embodied phases followed by energy used for installation. Of the raw materials used, pMDI contributes about 40 to 45%, followed by polyols (30 to 40%) and flame retardants (5 to 20%). When the use phase energy savings are considered, the raw materials contribution is even less than the embodied contribution with the contributions of individual materials even correspondingly lower. For example, because the entire embodied energy contribution of insulation in the life cycle for a house with ccSPF ranges from 3% (Houston) to 1% (Minneapolis), reducing the energy contributed by the raw materials would have no appreciable impact on the spray foam life cycle energy.

6.4.2 Climate Change

In the embodied phases, the GHGs contributed by ocSPF foam are relatively negligible compared to residential ccSPF foam and roofing foam, as water is used as the blowing agent for ocSPF foam. Based on an assumed 50% emissions loss for ccSPF and roofing foam, the blowing agent HFC-245fa contributes about 85% of the GHGs in the embodied phases. The 50% emissions rate loss of HFC-245fa is based on 10% of the blowing agent lost during installation. Of the remaining 40%, it is assumed that 60% is lost over the lifetime of the product and 40% at end of life. This means that 24% is lost during use on the building and 16% at end of life in a landfill (PE International, 2012).

When the use phase GHG avoided is taken into account, the contribution of HFC-245fa to the total life cycle GHG for a house ranges from 11% (Houston) to 4% (Minneapolis) for ccSPF. Replacement of this blowing agent in ccSPF with one having a negligible GWP would result in significantly lower GHG embodied/avoided ratios. This would be more in line with the GHG embodied/avoided ratio for ocSPF insulated houses, where the embodied to avoided ratios range from 1% (Houston) to 0.4% (Minneapolis). When low-GWP blowing agents are considered, the embodied contribution from ccSPF is slightly greater due mainly to the higher density of ccSPF versus ocSPF. These results have been confirmed by analysis (Bogdan et al., 2012).

At the time of this writing, low GWP blowing agents have been developed by several manufacturers and are in the process of being commercialized for spray foam applications. For example, the GWP of HFO-1336mzz-Z has been cited in the literature as 8.9 kg CO_2-equivalent/kg (Baasondorj, M., et al., 2011). Moreover, a life cycle assessment of this new low-GWP blowing agent indicates that the manufacturing burdens for a spray foam formulation using HFO-1336mzz-Z are similar to and do not dramatically increase compared to a spray foam formulation using conventional blowing agents (Johnas et al., 2011). The GWP of HFO-1233zd, another next-generation blowing agent for closed-cell SPF, has a reported GWP of 7.0 CO_2-equivalent/kg (Bogdan,M., et al., 2012). This paper, which performs a direct substitution of HFC-245fa with HFO-1233zd in an existing formulation, shows a significant reduction of embodied GWP for closed-cell foams. Detailed reassessment of the spray foam life cycle using the new low-GWP blowing agents which may include minor B-side formulation adjustments, is an area for future study when these materials become broadly commercialized as early as 2013.

6.4.3 Acidification, Eutrophication, Ozone Depletion, and Smog Creation

The trends for environmental impacts such as acidification, eutrophication, ozone depletion, and smog creation generally are similar to those for energy and climate change. Regarding embodied phases, across all types of foam, raw materials make up about 91% to 92% of the acidification, eutrophication, and smog creation and over 99% of the ozone depletion in the embodied phases. Of the raw materials used, pMDI contributes most of the impacts followed by polyols and flame retardants. When the magnitude of the use phase impacts avoided are considered, the raw materials contribution is even less than the embodied contribution, with the contributions of individual materials even correspondingly lower. Considering the raw materials contribution and results in Table 5-3 for a house with ccSPF, for example, the embodied to avoided impacts range from a maximum of 8% (Richmond) to a minimum of 1.3% (Minneapolis). Thus, reducing the impacts contributed by the raw materials would have no appreciable effect on the overall spray foam life cycle impact results.

Appendices

Appendix A: Impact Category Payback Results for Residential Housing & Commercial Roofing

Appendix A provides further details of saved or avoided impacts to embodied ratios, as well as the payback periods, for each impact category separately.

Life Cycle Primary Energy Demand from Resources

Table A-1 Life Cycle Primary Energy from Resources, 60 Years

BUILDING TYPE	ENERGY PAYBACK	HOUSTON	RICHMOND	MINNEAPOLIS
Residential Insulation	ocSPF-Saved/Embodied	63.7	127.6	194.1
	ocSPF-Payback (Yr)	0.9	0.5	0.3
	ccSPF-Saved/Embodied	32.1	64.2	97.8
	ccSPF-Payback (Yr)	1.9	0.9	0.6
Commercial Roofing	R4-R20 Saved/Embodied	55.0	56.1	66.2
	R4-R20 Payback (Yr)	1.1	1.1	0.9
	R12-R20 Saved/Embodied	30.2	28.1	28.6
	R12-R20 Payback (Yr)	2.0	2.1	2.1

Residential Housing

There is an overwhelming life cycle energy savings when either ocSPF (low-density) or ccSPF (medium-density) is applied to a residential house in each of the climate zones. Thus, the net life cycle energy is positive as there is much greater energy saved in use compared to the relatively small amount of embodied energy "invested" in making, installing, and disposing of the insulation. For example, the net life cycle energy resulting from installing ocSPF spray foam insulation on a new house in Richmond versus a base case of no cavity insulation is 6,861,794 MJ - 53,791 MJ, or 6,808,003 MJ saved. These values demonstrate that the use phase of spray foam insulation is by far the dominant phase in the life cycle and that the contributions of the embodied phases are minimal. Even if the embodied energy were reduced to zero, the impact of such a reduction on the total life cycle energy would be negligible.

Table A-1 demonstrates this point further as the energy saved when using ocSPF foam insulation is from approximately 64 to 194 times more than the embodied energy used to make, install, and dispose of the ocSPF spray foam at end of life. The payback period to recover the energy embodied in the ocSPF foam is less than one year in all locations.

Similar to the ocSPF insulation life cycle energy results, there is an overwhelming net positive life cycle energy savings when ccSPF spray foam is applied to a residential house. As a result of differences in formulation and density, the embodied energy associated with ccSPF foam is about twice as much compared to ocSPF foam and therefore the saved/embodied ratios are half that of ocSPF and the payback period is about two times greater. However, in all cases, the use phase energy savings are significantly greater than the embodied phases as the energy saved is approximately 32 to 98 times more than the embodied energy used to make, install, and manage the closed-cell spray foam at end of life.

Commercial Roofing

The commercial roofing retrofit cases show the effect of increasing the baseline insulation from R4 to R20 (increase of R16) and from R12 to R20 (increase of R8). The embodied energy of the SPF roofing insulation is based on a layer of R16 and R8, respectively, over a base layer of existing R4 or R12 insulation, which could be of any type.

Again, the energy saved is significantly greater than the embodied energy, ranging from approximately 55 to 66 for the R4 baseline to R20 (R16 additional) retrofit and the payback period is about one year. As expected, the saved/embodied ratio is roughly one-half that amount for the R12 to R20 (R8 additional) retrofit and the payback is corresponding twice as much, or approximately two years.

Life Cycle Climate Change

Table A-2 Life Cycle Greenhouse Gas Emissions, 60 Years

BUILDING TYPE	GHG PAYBACK	HOUSTON	RICHMOND	MINNEAPOLIS
Residential Insulation	ocSPF-Avoided/Embodied	92.3	164.4	248.3
	ocSPF-Payback (Yr)	0.7	0.4	0.2
	ccSPF-Avoided/Embodied	7.6	13.6	20.5
	ccSPF-Payback (Yr)	7.9	4.4	2.9
Commercial Roofing	R4-R20 Avoided/Embodied	14.9	14.8	16.8
	R4-R20 Payback (Yr)	4.0	4.1	3.6
	R12-R20 Avoided/Embodied	8.2	7.5	7.3
	R12-R20 Payback (Yr)	7.3	8.0	8.3

Residential Housing

In the case of ocSPF insulation, the GHGs avoided in the use phase range from over 90 to almost 250 times the GHGs associated with the embodied phases and the payback period is about half a year or less. The results for ccSPF insulation are significantly different for the same scenarios as the GHGs avoided in the use phase range from only 8 to 20 times the GHGs associated with the embodied phases and the GHG payback period for ccSPF insulation is a correspondingly higher three to eight years.

The longer GHG payback for ccSPF compared to ocSPF insulation results from the relatively high GWP factor for blowing agent used in ccSPF insulation (approximately 1000) compared to the GWP factor for water used as the blowing agent in ocSPF insulation (negligible). Most of the GHG associated with ccSPF insulation results from the assumed release of 50% of the blowing agent during the product's life cycle. Nevertheless, the GHG avoided in the use phase of ccSPF insulation are still noticeably greater than the embodied GHGs and the GHG payback periods are all well under 10 years.

Commercial Roofing

Because SPF roofing insulation foam components are currently manufactured with a the same high GWP blowing agent used in ccSPF foam for residential housing applications (and the release rate of blowing agent during the life cycle is assumed also at 50%), the GHG avoided/embodied ratios for roofing SPF are similar to the ccSPF values seen in residential housing. Installing an additional R16 of roofing SPF insulation results in a GHG avoided to embodied ratio of approximately 15, while adding an additional R8 of roofing SPF insulation yields a GHG avoided to embodied ratio of about half that amount, as expected. The same trend that is roughly proportionate to the R-value of the additional insulation is also seen in the payback period, which is about twice as high for the R8 compared to the R16 scenario. Again, the GHGs avoided in the use phase of roofing insulation are still noticeably greater than the embodied GHGs and the GHG payback periods are less than 5 years for the R4 to R20 retrofit and under 10 years for the R12 to R20 retrofit.

Life Cycle Acidification

Table A-3 Life Cycle Acidification, 60 Years

BUILDING TYPE	AP PAYBACK	HOUSTON	RICHMOND	MINNEAPOLIS
Residential Insulation	ocSPF-Avoided/Embodied	133.9	85.2	112.2
	ocSPF-Payback (Yr)	0.4	0.7	0.5
	ccSPF-Avoided/Embodied	64.4	40.9	53.9
	ccSPF-Payback (Yr)	0.9	1.5	1.1
Commercial Roofing	R4-R20 Avoided/Embodied	105.9	88.5	70.6
	R4-R20 Payback (Yr)	0.6	0.7	0.8
	R12-R20 Avoided/Embodied	56.9	46.0	30.8
	R12-R20 Payback (Yr)	1.1	1.3	1.9

Residential Housing

Unlike energy and GHG use phase results, where Houston had lower use phase values compared to the other cities, AP is relatively higher in Houston as a result of high electricity use mainly for air conditioning combined with an electricity AP factor (0.0442 moles H+ -equivalent/MJ) that is 10 times greater than the natural gas AP factor (0.00451 H+ moles-equivalent/MJ). Despite the much higher AP factor for electricity, the AP avoided in Minneapolis is the greatest as 26 times more natural gas energy is used for heating in that climate compared to the house's energy use from electricity.

As shown in Table A-3 for ocSPF insulation, the AP avoided in the use phase ranges from about 112 to over 134 times the AP associated with the embodied phases and the payback period is about half a year or less in all zones. The AP avoided to embodied results for ccSPF insulation are somewhat lower versus ocSPF insulation, despite that fact that thicker and higher volume (1.7 times the cubic feet) of ocSPF insulation is required to have the same R-value as ccSPF insulation. This effect of the higher insulation volume for ocSPF is overshadowed by a density of ccSPF that is about 3.5 times greater than for ocSPF, and thus the ccSPF embodied AP is about twice as high compared to ocSPF and the ccSPF payback periods are correspondingly twice as high versus ocSPF.

Commercial Roofing

The trend among the climate zones is generally opposite of the energy and GHG results, where Houston had lower use phase values compared to the other cities. This is because the commercial building electrical energy use in Houston is about 4 times greater than the natural gas energy used and, combined with an electricity AP factor that is 10 times greater than the natural gas AP factor, this results in significantly greater AP avoided in Houston compared to the other two zones.

As shown in Table A-3, the AP avoided for the R4 to R20 retrofit in the use phase ranges from about 71 to 106 times the AP associated with the embodied phases and the payback period is about half a year in all zones. The AP avoided to embodied results for the R12 to R20 retrofit insulation are, as expected, roughly half compared to the R4 to R20 retrofit and the payback period is corresponding twice as high for the R12 to R20 case. This general trend is expected in light of the embodied AP doubling from installing an incremental R8 to R16 insulation, respectively.

Life Cycle Eutrophication

Table A-4 Life Cycle Eutrophication, 60 Years

BUILDING TYPE	EP PAYBACK	HOUSTON	RICHMOND	MINNEAPOLIS
Residential Insulation	ocSPF-Avoided/Embodied	50.1	54.3	78.2
	ocSPF-Payback (Yr)	1.2	1.1	0.8
	ccSPF-Avoided/Embodied	22.8	24.7	35.6
	ccSPF-Payback (Yr)	2.6	2.4	1.7
Commercial Roofing	R4-R20 Avoided/Embodied	36.0	32.3	30.7
	R4-R20 Payback (Yr)	1.7	1.9	2.0
	R12-R20 Avoided/Embodied	19.5	16.6	13.3
	R12-R20 Payback (Yr)	3.1	3.6	4.5

Residential Housing

Similar to energy and GHG use phase results, Houston yields lower use phase values compared to the other cities, as EP is relatively lower in Houston compared to the other zones despite high electricity use and an electricity EP factor that is 4.5 times greater than the natural gas EP factor. This is because the EP associated with natural gas energy use in Richmond (14 times more natural gas energy vs. electricity) and especially Minneapolis (26 times more natural gas energy vs. electricity) overwhelm the EP value for Houston, where the house consumes no natural gas.

As shown in Table A-4 for ocSPF insulation, the EP avoided in the use phase ranges from about 50 to 78 times the EP associated with the embodied phases and the payback period is about a year in all zones. The EP avoided/embodied results for ccSPF insulation are somewhat lower versus ocSPF insulation despite that fact that thicker and higher volume (1.7 times the cubic feet) of ocSPF insulation is required to have the same R-value as ccSPF insulation. This effect of the higher insulation volume for ocSPF is overshadowed by a density of ccSPF that is about 3.5 times greater than for ocSPF. Thus the ccSPF embodied EP is about twice as high compared to ocSPF and the ccSPF payback periods are correspondingly twice as high versus ocSPF as well. The difference in the EP factors on a mass basis for the embodied ocSPF and ccSPF are fairly similar, differing by about 5%, and thus do not have any appreciable effect on the values.

Commercial Roofing

The trend among the zones is generally opposite of the energy and GHG results, where Houston had similar/lower use phase values compared to the other cities. Again, similar to AP, this is because the commercial building electrical energy use in Houston is about 4 times greater than the natural gas energy used, and, combined with an electricity EP factor that is 4.5 times greater than the natural gas EP factor, this results in a somewhat greater EP avoided in Houston compared to the other two zones. However, the EP avoided in Houston is only 12% to 18% greater than the EP avoided in the other cities as there is somewhat lower electricity use but greater natural gas used in the Richmond and Minneapolis cases versus Houston.

As shown in Table A-4, the EP avoided for the R4 to R20 retrofit in the use phase ranges from about 31 to 36 times the EP associated with the embodied phases and the payback period is two years or less in all zones. The EP avoided to embodied results for the R12 to R20 retrofit insulation are, as expected, roughly half compared to the R4 to R20 retrofit, and the payback period is corresponding twice as high for the R12 to R20 case. This general trend is expected in light of the embodied EP doubling from installing an incremental R8 to R16 insulation, respectively.

Life Cycle Ozone Depletion

Table A-5 Life Cycle Ozone Depletion, 60 Years

BUILDING TYPE	ODP PAYBACK	HOUSTON	RICHMOND	MINNEAPOLIS
Residential Insulation	ocSPF-Avoided/Embodied	34.7	23.2	30.9
	ocSPF-Payback (Yr)	1.7	2.6	1.9
	ccSPF-Avoided/Embodied	18.8	12.6	16.7
	ccSPF-Payback (Yr)	3.2	4.8	3.6
Commercial Roofing	R4-R20 Avoided/Embodied	29.4	24.7	20.0
	R4-R20 Payback (Yr)	2.0	2.4	3.0
	R12-R20 Avoided/Embodied	15.8	12.8	8.7
	R12-R20 Payback (Yr)	3.8	4.7	6.9

Residential Housing

Unlike energy and GHG use phase results, where Houston had lower use phase values compared to the other cities, ODP is relatively higher in Houston as a result of high electricity use mainly for air conditioning combined with an electricity ODP factor that is nine times greater than the natural gas ODP factor. Despite the much higher ODP factor for electricity, the ODP avoided in Minneapolis is the greatest, as 26 times more natural gas energy is used for heating in that climate compared to the house's energy use from electricity. This trend is similar to that for AP as previously described, as the AP factor that is 10 times greater than the natural gas AP factor.

As shown in Table A-5 for ocSPF insulation, the ODP avoided in the use phase ranges from about 23 to 35 times the ODP associated with the embodied phases and the payback period is about two to three years. The ODP avoided to embodied results for ccSPF insulation are somewhat lower versus ocSPF insulation, despite that fact that thicker and higher volume (1.7 times the cubic feet) of ocSPF insulation is required to have the same R-value as ccSPF insulation. This effect of the higher insulation volume for ocSPF is overshadowed by a density of ccSPF that is about 3.5 times greater than for OC. As a result, the ccSPF payback periods are about twice as high versus ocSPF.

Commercial Roofing

The trend among the zones is generally opposite of the energy and GHG results, where Houston had lower use phase values compared to the other cities. The trend is for ODP is similar to the trend for AP due to the significantly higher characterization factors of these categories for electricity versus natural gas. Because the commercial building electrical energy use in Houston is about four times greater than the natural gas energy used, combined with an electricity ODP factor that is nine times greater than the natural gas ODP factor, the result is significantly greater ODP avoided in Houston compared to the other two zones.

As shown in Table A-5, the ODP avoided for the R4 to R20 retrofit in the use phase ranges from about 20 to 30 times the ODP associated with the embodied phases and the payback period is about two to three years in all zones. The ODP avoided to embodied results for the R12 to R20 retrofit insulation are, as expected, roughly half compared to the R4 to R20 retrofit and the payback period is corresponding twice as high for the R12 to R20 case. This general trend is expected in light of the embodied AP doubling from installing an incremental R8 to R16 insulation, respectively.

Life Cycle Smog Creation

Table A-6 Life Cycle Smog Creation, 60 Years

BUILDING TYPE	SCP	HOUSTON	RICHMOND	MINNEAPOLIS
Residential Insulation	ocSPF-Avoided/Embodied	90.1	109.0	159.0
	ocSPF-Payback (Yr)	0.7	0.6	0.4
	ccSPF-Avoided/Embodied	44.7	54.1	79.0
	ccSPF-Payback (Yr)	1.3	1.1	0.8
Commercial Roofing	R4-R20 Avoided/Embodied	70.7	64.8	63.9
	R4-R20 Payback (Yr)	0.8	0.9	0.9
	R12-R20 Avoided/Embodied	38.3	33.1	27.8
	R12-R20 Payback (Yr)	1.6	1.8	2.2

Residential Housing

Similar to energy and GHG use phase results, as well as the EP results, Houston yields lower use phase values compared to the other cities as SCP is relatively lower in Houston compared to the other zones despite high electricity use and an electricity SCP factor that almost 4 times greater than the natural gas SCP factor. This is because the SCP associated with natural gas energy use in Richmond (14 times more natural gas energy versus electricity) and especially Minneapolis (26 times more natural gas energy versus electricity) overwhelms the SCP value for Houston, where the house consumes no natural gas.

As shown in Table A-6 for ocSPF insulation, the SCP avoided in the use phase ranges from about 90 to 159 times the SCP associated with the embodied phases and the payback period is about half a year in all zones. The SCP avoided to embodied results for ccSPF insulation are somewhat lower versus ocSPF insulation despite that fact that thicker and higher volume (1.7 times the cubic feet) of ocSPF insulation is required to have the same R-value as ccSPF insulation. This effect of the higher insulation volume for ocSPF is overshadowed by a density of ccSPF that is about 3.5 times greater than for ocSPF and thus the ccSPF embodied SCP is about twice as high compared to ocSPF and the ccSPF payback periods are correspondingly twice as high versus ocSPF as well. The difference in the SCP factors on a mass basis for the embodied ocSPF and ccSPF are fairly similar, differing by about 2.5 %, and thus do not have any appreciable effect on the values.

Commercial Roofing

The trend among the zones is generally opposite of the energy and GHG results, where Houston had similar or lower use phase values compared to the other cities, but the trend is similar to the EP results because the ratios of the electricity to natural gas energy factors are both about four for EP and SCP. Again, this is because the commercial building electrical energy use in Houston is about four times greater than the natural gas energy used, and, combined with an electricity ACP factor that is four times greater than the natural gas SCP factor, this results in a somewhat greater SCP avoided in Houston compared to the other two zones. However, the SCP avoided in Houston is only about 10% greater than the SCP avoided in the other cities as there is somewhat lower electricity use but greater natural gas used in the Richmond and Minneapolis cases versus Houston.

As shown in Table A-6, the SCP avoided for the R4 to R20 retrofit in the use phase ranges from about 64 to 71 times the SCP associated with the embodied phases and the payback period is less than one year in all zones. The SCP avoided to embodied results for the R12 to R20 retrofit insulation are, as expected, roughly half compared to the R4 to R20 retrofit and the payback period is corresponding twice as high for the R12 to R20 case. This general trend is expected in light of the embodied EP doubling from installing an incremental R8 to R16 insulation, respectively.

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