Online Exclusive

Unlocking Carbon Savings with Plastic Insulation Materials

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PLASTIC INSULATION IS typically composed of a plastic polymer, such as polyurethanes or polystyrenes, a blowing agent, such as chlorofluorocarbons (CFCs), a surfactant, and other flame retardants or additives. The application of insulation in homes evolved from hay to fiberglass in the 1930s, followed by the shift to plastic insulation in the 1970s.[1, 2]

The method of determining the environmental impact of plastic insulation materials is through a life-cycle assessment (LCA), which is the quantified analysis of the material and energy inventories and potential environmental impacts of a product through the various stages of that product's life. An LCA consists of four phases: goal and scope, life-cycle inventory, life-cycle impact assessment, and interpretation of the results. In the building sector, the life-cycle of insulation products is typically depicted in an environmental product declaration (EPD) that communicates the verifiable results of an LCA. The life-cycle of an insulation product includes four stages: product manufacture, construction, use, and end of life. A fifth stage, depicted by Module D in Figure 1, quantifies potential benefits and impacts beyond the building's system boundary and is often excluded from the scope of EPDs. The life-cycle stages are divided further into substages called modules shown in **Fig. 1** module A1 through module C4. Figure 1 also depicts the four more-common types of life-cycle scopes: cradle-to-gate, cradle-to-site, cradle-to-grave, and cradle-to-cradle.

EPDs for insulation products report various environmental impact categories, including the embodied carbon of the insulation material, which is calculated as the global warming potential (GWP) and expressed as kg CO_2e or kilograms of carbon dioxide equivalent. This article focuses on the embodied carbon of four insulation types: expanded polystyrene (EPS), extruded polystyrene (XPS), spray foam (SPF), and polyisocyanurate (PIR). EPS is made up of closed-cell foam plastic beads molded into a rigid board. XPS is an extruded closed cell insulation product that comes in the form of boards. SPF is foamed in place at the job site; it comes in open cell and closed cell material types which expands when its two components react when combined in a spray gun. PIR or polyiso, is a closed-cell rigid foam board insulation consisting of a foam core typically between two facers. The functional unit is m^2 of insulation based on an RSI value of 1 based on a service life of 75 years for each of the four insulation types. RSI is variable used in the International System of Units (SI) for thermal resistance. RSI can be converted to *R*-value, the Imperial Units (IP) variable, by multiplying the RSI value by 5.678. Thus, all analyzed environmental impacts are reported based on this functional unit. For example, the GWP is reported kg CO_2e/m^2 of insulation based on an RSI value of 1 based on a service life of 75 years. Data were collected from primary sources, EPDs from various years and product category rules (PCRs), and peer-reviewed reports. The embodied carbon data points were then grouped by their formulation; the most recent formulation of each material from a producer was used.

Over the last several decades, plastic insulation has included blowing agents from chlorofluorocarbons (CFCs), to hydrochlorofluorocarbons (HCFCs), to hydrofluorocarbons (HFCs), and

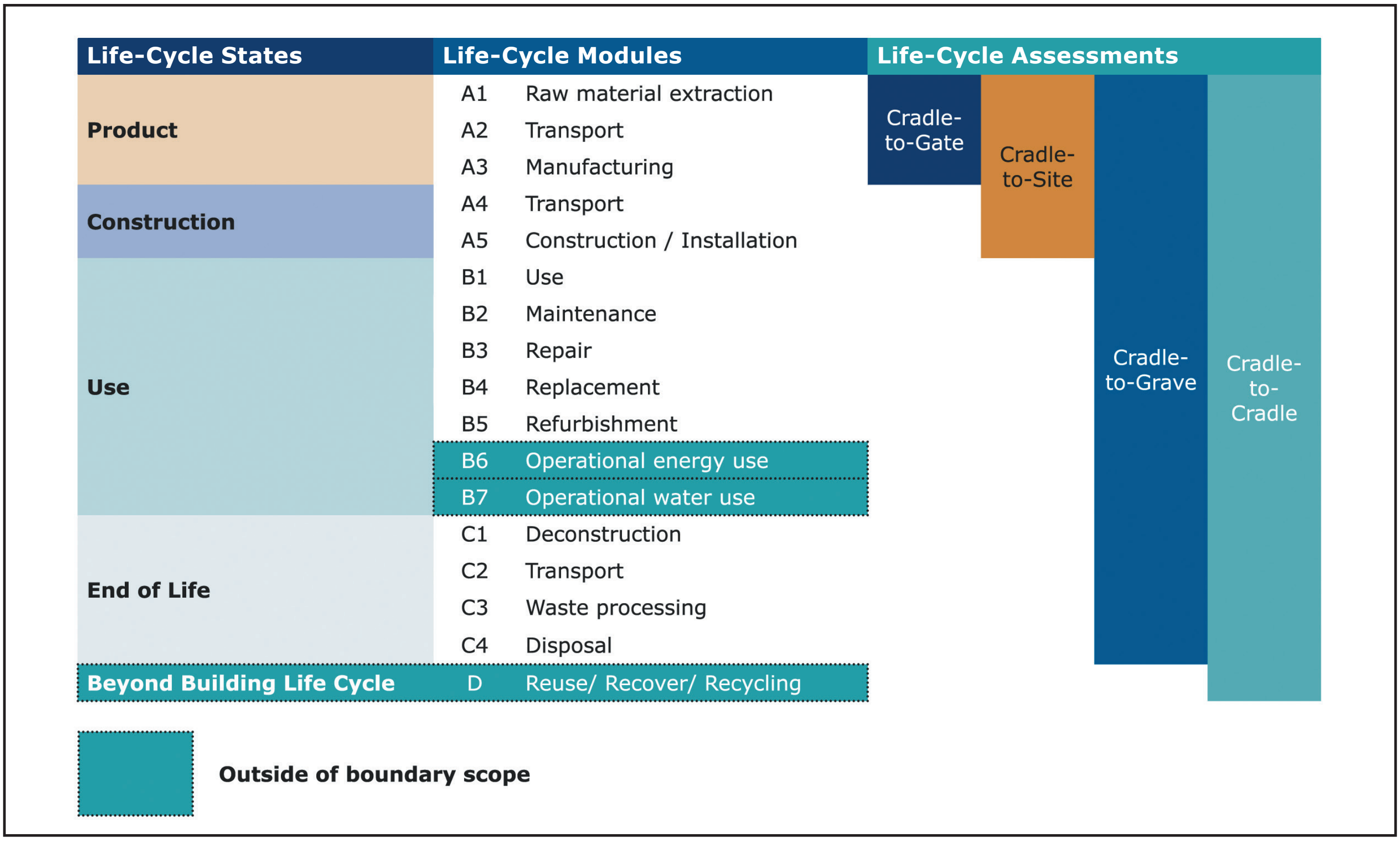

Figure 1. *Displays the life-cycle modules for each life-cycle stage of the insulation and common scopes of life-cycle assessment.*

hydrofluoroolefins (HFOs). Part I of the "Results and Discussion" section describes the shift to blowing agents with lower greenhouse gas (GHG) emissions and ultimately lower embodied carbon. The decreasing embodied carbon of plastic insulation materials was the result of product reformulations driven by global concern regarding the environmental impact of blowing agents. Despite the globally publicized phase out of blowing agents with high GWPs, plastic insulation continues to be scrutinized for its supposed high embodied carbon and related impacts. The limited understanding of embodied carbon improvements inhibits the ability of the plastics insulation industry to inform GWP-related policy and develop solutions surrounding decisions on the sustainability of plastic insulation. Additionally, there are insufficient data on the total carbon impacts of insulation, including the embodied carbon of insulation material and the carbon benefits of these materials. Here, total carbon impact is defined as the net impact of the embodied carbon investment and the operational carbon savings associated with a material, as shown in **Fig. 2**.[3] Therefore, this two-part report aims to A) highlight the historical reductions in the embodied carbon of four insulation types and B) evaluate the life-cycle energy and GHG savings attributed to the application of plastic insulation materials in both residential and commercial building enclosures. Figure 2 demonstrates the inputs required to calculate the total carbon of a material, which is the sum of the embodied carbon of a material and the operational carbon savings of the same material.

EXPERIMENTAL

Part I

The embodied carbon of each insulation type is determined by calculating the GWP of the insulation products in accordance with the *Product Category Rules (PCR) Guidance for Building Related Products and Services Part B: Building Envelope Thermal Insulation EPD Requirements* UL 10010-1.[4] The PCR includes modules A1-A5, B1-B5, and C1-C4 (Fig. 1). Impacts of other modules can be voluntarily included in the EPD but are not included for the purposes of our analysis. The EPDs are typically conducted by an insulation association or insulation manufacturer with the assistance of a third-party consultant or LCA expert. Although several potential environmental impacts are included in a product's EPD, this report focuses on GHGs. GHGs are gases that absorb and trap

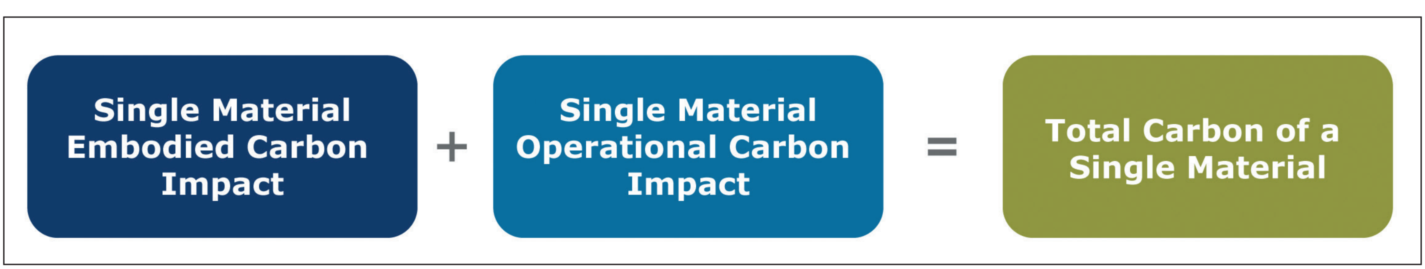

Figure 2. *Total carbon of a material evaluates the net greenhouse gas emissions from a product or material's embodied carbon and emissions savings attributed to the operational carbon benefits realized after installation and during the building's use.*

heat in the atmosphere; the most common GHGs include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The GHGs are measured in a metric called global warming potential (GWP). GWP is used to measure the impact of different gases on one shared scale, due to gases having different effects on global warming. The two main ways GHGs have variable effects on global warming are their abilities to absorb energy and the amount of time they stay in the atmosphere. GWP measures the amount of energy one ton of a gas will absorb over a certain amount of time compared to the amount of energy one ton of CO_2 will absorb over the same amount of time. As mentioned previously, GWP is measured as kilograms (kg) of CO_2 equivalent, which allows different GHGs to be compared on the same scale.

To compare the changes in the GWP of the four plastic insulation types, data were collected from primary sources through a survey. Insulation manufacturers were requested to provide current and historical life-cycle data, specifically embodied carbon data along with its associated PCR version as applicable and any notable changes that may have caused the change in embodied carbon from one PCR or product formulation to the next. Additional information was collected from industry and producer EPDs available on the Building Transparency EC3 database.[5] Data from peer-reviewed sources were also incorporated where applicable to maintain the parameters of the study for North American applications.

Part II

To develop new data and gain a more current perspective on the net, or total carbon impacts of plastic insulation materials, specifically XPS, EPS, SPF, and PIR, a modeling project was conducted by ICF International Inc. This project, "Determination of Total Carbon Impact of Plastic Insulation Materials," examined the energy and operational carbon impacts associated with these four plastic insulation materials throughout their useful life using conservative assumptions, including thermal resistance properties, climate zones, building types, and grid makeup.[6] The model results were compared to the embodied carbon investment of the insulation materials in the prototype buildings to establish an understanding of the total carbon payback and total carbon avoidance (embodied carbon investment to operational carbon savings).

A case study by Franklin Associates, "Plastic Energy and Greenhouse Gas Savings Using Rigid Foam Sheathing Applied to Exterior Walls of Single-Family Residential Housing in the U.S. and Canada," found favorable energy and carbon payback time frames.[7] While this study used different modeling assumptions than the recent ICF study and was conducted nearly two decades prior, the results were consistent. The Franklin study showed that by adding an additional ⅝ in (16 mm) of exterior rigid foam insulation to a home with a service life of 50 years, a GHG payback ranging from 12.5 years in the US to 3 years in Canada could be achieved, despite the higher embodied carbon of insulation materials at that time.

Another research report in the *Journal of Industrial Ecology* (JIE), "Life Cycle Greenhouse Gas Emissions Reduction from Rigid Thermal Insulation Use in Buildings," published in 2011, found an average GHG savings to embodied carbon ratio of 48:1.[8] As with the Franklin study, this study used different modeling assumptions than the ICF study but found comparable significant total carbon benefits of plastic insulation materials when considering the full life-cycle of the building. It's important to note the GHG emissions data per functional unit in the 2011 study were not subjected to the same third-party analysis or PCR as with the ICF study.

There are a handful of other industry-wide and manufacturer-specific LCAs that model total carbon benefits, but the majority are limited to a single insulation type or building application, further emphasizing the need for recent, and more extensive studies on the total carbon benefits of plastic insulation.

The ICF study, included current plastic insulation embodied carbon data, projected grid emissions data based on the National Renewable Energy Lab (NREL) Cambium scenarios, Climate Zones 3 and 5, and Department of Energy (DOE) residential two-story home and medium office building prototypes.[9] ICF utilized DOE's Energy Plus software to model the energy data. ICF also calculated the total carbon impacts of the insulation materials in the modeled buildings and used current and projected grid emissions data to determine the GWP impacts. Using the data, ICF calculated the plastic insulation material GWP payback and GWP avoidance ratios using Cambium High, Medium, and Low Cost of Conversion to Renewable Energy grid projections. The data were then compared to the embodied carbon investment in these materials in prototype buildings so that an understanding of GWP payback and GWP avoidance could be established.

The US is segmented into eight different climate zones, represented by a number 1-8, and three categories based on moisture levels, denoted by letters A, B, and C.[11] Climate Zones 3 and 5 were selected for the study because they are conservatively representative of heating and a cooling dominated regions of the U.S. (**Table 1**). These climate zones are also home to a large segment of the population and the representative cities are all found in the top 11 states for housing starts in 2022 according to the US Census Bureau Building Permits Survey.[10]

Representative thermo-physical properties were established in (**Table 2**). These values do not reflect all available or proprietary insulation properties. They are conservative representations of materials readily available in the US.

Table 1. Representative Climate Zones 3 and 5 Modeling Assumptions

Climate Zone	Representative City	Weather Location	HDD65	CDD65
3A	Atlanta, Georgia	Atlanta/Hartsfield Jackson International Airport, Georgia	2,498	2,099
3B	El Paso, Texas	El Paso International Airport, Texas	2,012	2,972
3C	San Diego, California	San Diego/Brown Field Municipal Airport, California	1,377	763
5A	Buffalo, New York	Buffalo Niagara International Airport, New York	6,242	769
5B	Denver, Colorado	Denver/Aurora/Buckley AFB, Colorado	5,737	832
5C	Port Angeles, Washington	Port Angeles/William R Fairchild International Airport, Washington	5,488	20

Note: HDD65 = Heating Degree Days below 65°F (18°C); CDD65 = Cooling Degree Days above 65°F (18°C).

Table 2. Representative Thermo-physical Properties of Plastic Insulation Materials

Insulation Material	*R*-value per inch thickness	Thermal Conductivity Btu/h·ft·°F (W/m·K)	Density lb/ft³ (kg/m³)	Specific Heat Btu/lb·°F (J/kg·K)
XPS	5.00	0.01667 (0.02885)	1.56 (25)	0.36 (1500)
EPS	4.00	0.02083 (0.03606)	1.56 (25)	0.36 (1500)
Closed cell-SPF	6.50	0.01282 (0.02219)	2.18 (35)	0.35 (1450)
Open cell-SPF	3.50	0.02381 (0.04121)	2.18 (35)	0.35 (1450)
Polyisocyanurate	5.80	0.01437 (0.02487)	1.56 (25)	0.36 (1500)

Note: EPS = expanded polystyrene; SPF = spray foam; XPS = extruded polystyrene.

Table 3. Simulated Scenarios for Residential Prototype

Scenario	Description
R0	No Insulation (Baseline)
R1	Basement + Attic Insulation (No Wall Insulation)
R2	Wall + Attic Insulation (No Basement Insulation)
R3	Wall + Basement Insulation (No Attic Insulation)
R4	Whole Home Insulation

Table 4. Simulated Scenarios for Commercial Prototype

Scenario	Description
C0	No Insulation (Baseline)
C1	Slab + Roof Insulation (No Wall Insulation)
C2	Wall + Roof Insulation (No Slab Insulation)
C3	Wall + Slab Insulation (No Roof Insulation)
C4	Whole Office Insulation

Table 5. 2021 *International Energy Conservation Code* (IECC) Minimum Insulation *R* -values and Enclosure Components.[13]

Location	Climate Zone	
	3	5
Above-Grade Exterior Wall Insulation	*R*-13 oc-SPF/cc-SPF blend 50/50 in cavity, *R*-5ci XPS/EPS foam sheathing blend 50/50	*R*-13 oc-SPF/cc-SPF blend 50/50 in cavity, *R*-10ci XPS/EPS foam sheathing blend 50/50
Basement Exterior Wall Insulation	*R*-5ci exterior XPS	*R*-10ci exterior XPS, *R*-5ci interior XPS/EPS foam sheathing blend 50/50
Unvented Attic Insulation (Roof and Gable End Wall)		
Roof Insulation	*R*-38 cc-SPF, as allowed by IECC Section R402.2.1, assuming that insulation is applied to full *R*-value and over the top plate at the eaves.	*R*-49 cc-SPF, as allowed by IECC Section R402.2.1, assuming that insulation is applied to full *R*-value and over the top plate at the eaves
Gable End Wall Insulation	*R*-13 oc-SPF/cc-SPF blend 50/50 in cavity, *R*-5ci XPS/EPS foam sheathing blend 50/50	*R*-13 oc-SPF/cc-SPF blend 50/50 in cavity, *R*-10ci XPS/EPS foam sheathing blend 50/50

Note: cc = closed cell; ci = continuous insulation; EPS = expanded polystyrene; oc = open cell; SPF = spray foam; XPS = extruded polystyrene.

Table 6. ASHRAE 90.1-2019 Minimum Insulation *R*-values and Enclosure Components.[14]

Location	Climate Zone	
	3	5
Above-Grade Wall Insulation	Steel framed, *R*-13 cc-SPF in cavity, *R*-5ci PIR sheathing	Steel framed, *R*-13 cc-SPF in cavity, *R*-10ci PIR sheathing
Slab Insulation	None	*R*-15ci XPS foam sheathing for 24″ deep from top of slab down
Roof Insulation (Entirely Above Deck)	*R*-25ci PIR sheathing	*R*-30ci PIR sheathing

Note: cc = closed cell; ci = continuous insulation; PIR = polyisocyanurate; SPF = spray foam; XPS = extruded polystyrene.

Two prototype buildings were selected for the study, one residential and one commercial. Again, conservative prototypes were selected. The residential prototype selected was the DOE two-story home.[12] This is typically more conservative than the one-story home prototype due to its smaller square footage and area of thermal loss through the ceiling/roof. The commercial prototype selected was the medium office building. This prototype is typically more conservative than other larger, more energy intensive, buildings like schools and hospitals.

Four base modeling scenarios were developed for both residential and commercial. These scenarios are shown in **Tables 3** and **4**.

Plastic insulation types that are commonly used in these applications were used in the model. In some scenarios where one of two materials are typically used, their data were averaged ($^{50}/_{50}$ blend). The representative insulation types selected are shown in **Table 5** for residential and **Table 6** for commercial. For the residential model, the insulation configurations for both the roof deck and on the gable ends was defined. The insulation types specified for modeling purposes in this study are not representative of all potential plastic insulation materials that can be used in these applications.

These assumptions were used to inform the assembly thermal resistance values used in the EnergyPlus model.

A few changes were made to the EnergyPlus model to better represent the configuration of enclosure layers and the location of insulation elements. For example, the modeling of residential insulation at the roof deck versus the attic floor was used to simulate an unvented attic. These adjustments are described in detail in the ICF report.[6]

A 75-year useful life was assumed, which is the same service life assumption that is included in the PCR for thermal insulation materials.

There were 147 simulations modeled: 120 for residential and 27 for commercial. There were more simulations run for the residential model due to the 4 different heating systems (electric resistance, gas furnace, oil furnace, and heat pump) in the EnergyPlus model. Additional simulation details can be found in the ICF report.[6]

RESULTS AND DISCUSSION

Part I

While there are many factors that have led to reductions in the embodied carbon of insulation products, using lower GHG blowing agents are attributed to the most significant improvements. CFCs were first synthesized in the 1920s in a combined effort by Frigidaire, General Motors, and DuPont to replace less desirable substances with refrigerant qualities.[15] CFCs were utilized as blowing agents in foam insulation materials where they formed air-filled pockets that restricted heat transfer and reduced the density of the foam insulation. In 1974, scientists discovered the risk CFCs posed to the deterioration of the ozone layer upon their release. The depletion of ozone, a gas with ultraviolet radiation absorption properties, could increase the amount of radiation that reaches the earth's surface, subsequently heating the planet. Like the ozone-depleting characteristics of CFCs, these gases were determined to have a significant embodied carbon demonstrated by their high GWP. According to a study of the GHG emissions of rigid thermal insulation, a formulation of XPS (principle blowing agent CFC-12) used in North America from 1971-1989, had an embodied carbon of more than 900 kg CO_2e/m^2.[7]

As a result of rising concerns associated with the ozone-depleting nature of CFCs, a global environmental treaty, the *Montreal Protocol to Reduce Substances that Deplete the Ozone Layer*, was adopted in 1987.[16] The treaty outlined a plan to phase out several ozone depleting substances, including CFCs, by placing controls on the production and consumption of these substances. In the absence of CFCs two new classes of substances were created with similar insulating properties,

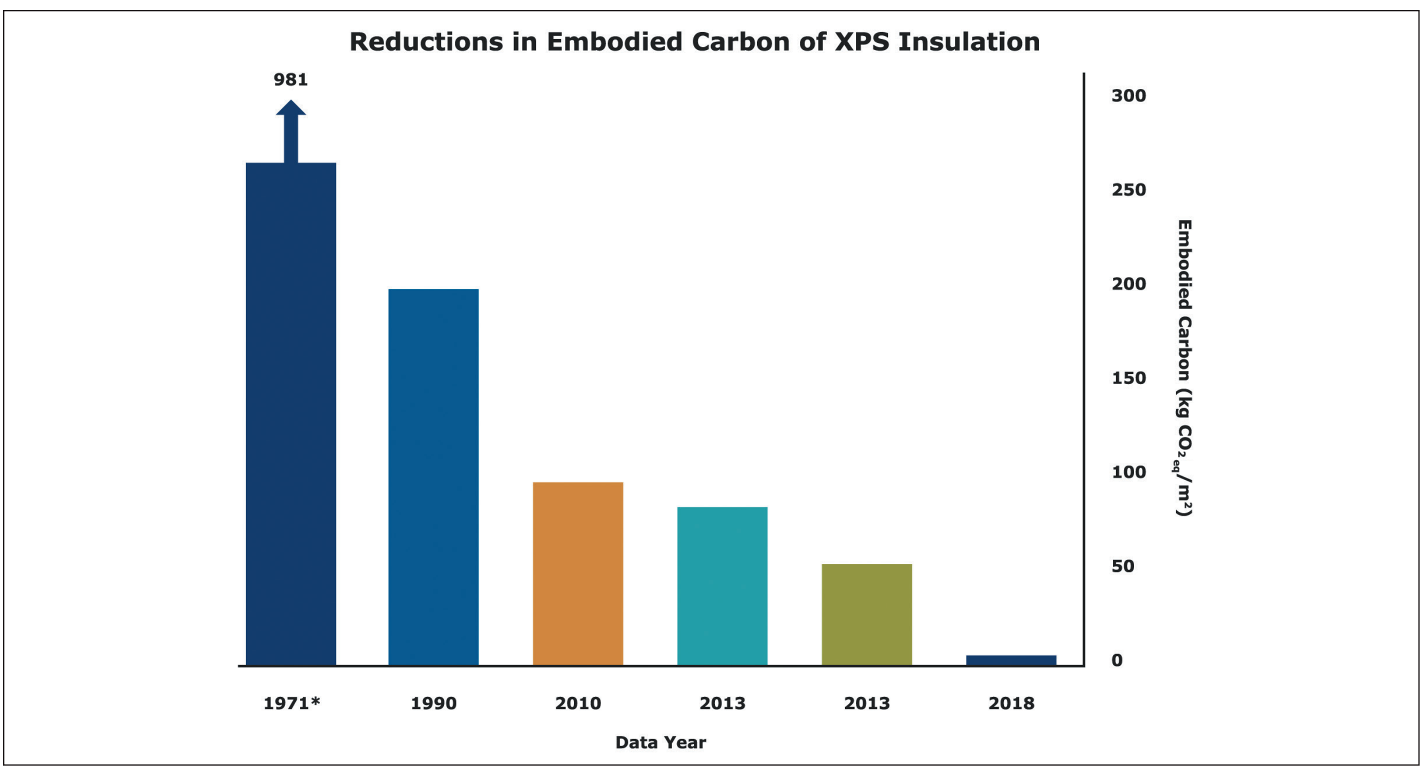

Figure 3. *Reductions in embodied carbon of extruded polystyrene (XPS) insulation based on formulations in 1971, 1990, 2010, 2013, and 2018. *The X-axis cuts-off at 300 kg CO_2e/m^2 to accommodate the more recent embodied carbon metrics that are significantly below 100 kg CO_2e/m^2. However, the actual embodied carbon for XPS in 1971 is shown within the data bar as 981 kg CO_2e/m^2.*

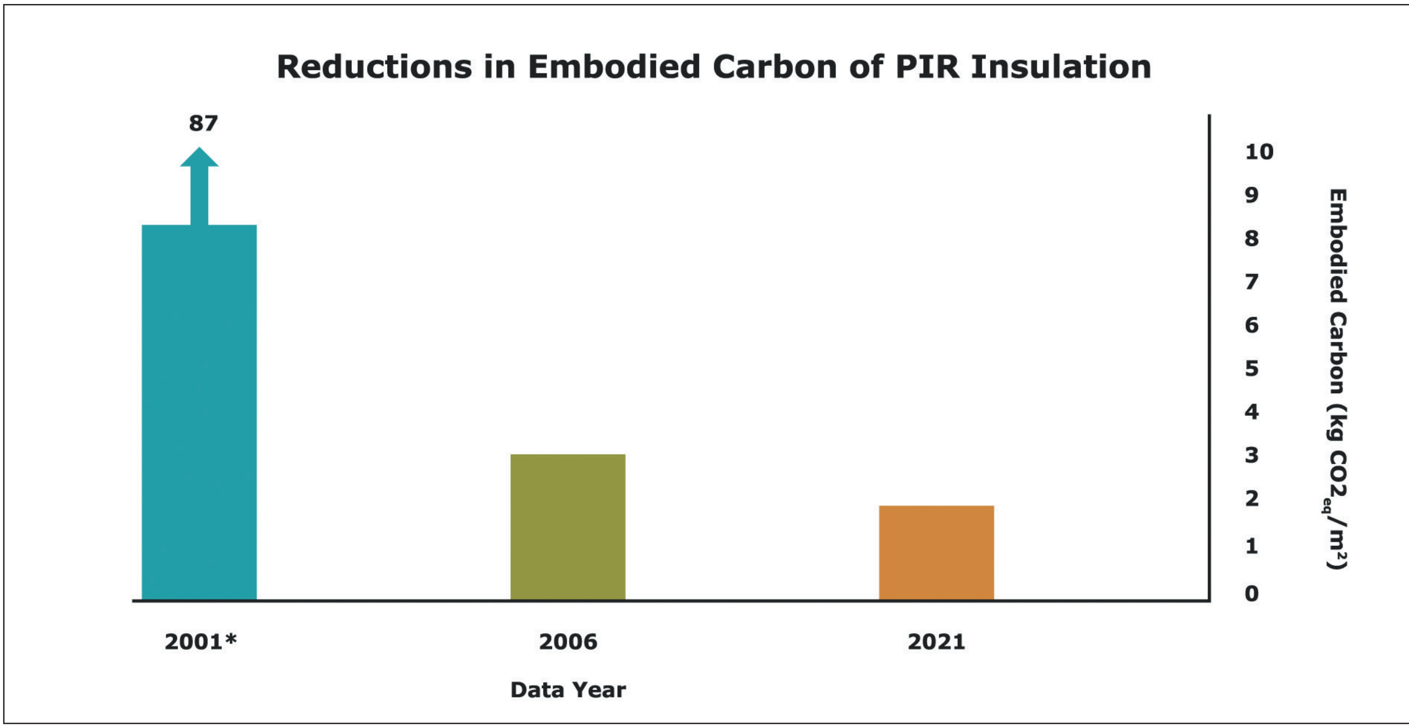

Figure 4. *Reductions in embodied carbon of polyisocyanurate (PIR) insulation based on formulations in 2001, 2006, and 2021. *The YX-axis cuts-off at 10 kg CO_2e/m^2 to accommodate the more recent embodied carbon metrics that are significantly below 10 kg CO_2e/m^2. However, the actual embodied carbon for PIR in 2001 is shown within the data bar as 87 kg CO_2e/m^2.*

HCFCs and HFCs. HCFCs proved to be beneficial substitutes with a significantly lower GWP than CFCs, as demonstrated by the 1990 formulation of XPS (principle blowing agent HCFC-142b) with a GWP of less than 230 kg CO_2e/m^2.

However, HCFCs had similar potential to CFCs to deplete the ozone layer, prompting an amendment to the Montreal Protocol outlining their planned phase out too. This precipitated the substitution of HCFCs with HFCs. While HFCs do not have ozone depleting properties, they have significant embodied carbon or GWPs that resulted in the adoption of the Kigali Amendment in 2016. This amendment outlines the plan to phase out HFCs before 2050, due to the high GWPs ranging from 12 to 14,800.[17] These substances will be replaced by lower GWP blowing agents, such as HFOs or pentanes.

Figure 3 showcases the reductions in embodied carbon of XPS insulation materials over the last several decades. The years indicated on the X-axis correlate to the year a new generation of XPS was introduced. The embodied carbon of XPS has been significantly reduced since 1971, primarily as a result of innovations in new blowing agents and polymers, production efficiencies, and material sourcing. While some product generations may overlap, the higher GWP materials are continuing to be phased out as the industry trends shift towards greater sustainability. Although the most recent formulation was introduced in 2018, more recent XPS products with EPDs published in 2021 and beyond, show a continual downward trend in the embodied carbon.

Similarly, **Figure 4** displays the reductions in embodied carbon of PIR insulation materials over the last several decades. The years indicated on the X-axis correlate to the year a new generation of PIR was produced. The embodied carbon of PIR has been reduced significantly since 2001, resulting from innovations in new blowing agents and polymers, production efficiencies, and material sourcing. While some product generations may overlap, the higher GWP materials are continuing to be phased out as the industry trends shift toward greater sustainability. Although the most recent formulation was introduced in 2006, more recent PIR products with EPDs published in 2021 and beyond, show a continual downward trend in the embodied carbon.

The scope of Part I included the embodied carbon of four types of plastic insulation. However, there was limited data publicly available that met the parameters of the study, including the functional unit and geographical location. Plastic insulation produced, transported, installed, and disposed of in other countries or regions, such as Europe, may have varying GWP results compared to plastic insulation materials produced in the US. This is because of potential differences in the grid's fuel sources, since some energy sources have higher emissions than others when combusted. Furthermore, expired EPDs are removed from databases and other building resources to ensure that only current data on the contents and embodied carbon of plastic insulation materials are communicated. While beneficial in reducing the communication of outdated metrics, this presents a challenge in collecting historical information. Additionally, the tracking of plastic insulation's embodied carbon through EPDs is a more recent process, further adding to the limited data available. However, it's important to recognize that other plastic insulation materials, including SPF and EPS, were not previously produced with high GWP components, such as CFCs, HCFCs, or HFCs. Moreover, the current EPDs for both EPS and SPF showcase embodied carbons comparable to most recent formulations of XPS and PIR. This emphasizes the continual trend for plastic insulation products to have low embodied carbon throughout their life-cycles.

Part II: Determination of Total Carbon Impacts

To determine the total carbon impacts associated with plastic insulation materials, the embodied carbon of the insulation materials, and the operational carbon savings associated with the modeled buildings were summed.

The operational energy consumption and savings were determined through the modeling for the various scenarios. Modeling was done using current heating and cooling system energy mixes and to simulate a future 100% heat pump conversion.

The total site energy use for each of the scenarios utilizing the current heating systems can be found in the ICF report.[6] From this consumption data, the energy savings of the insulation elements associated with each scenario were determined and summarized in **Table 7** (residential) and **Table 8** (commercial).

The ICF report noted, consistent with anomalies experienced with EnergyPlus, that the software seems to undervalue slab insulation contributions.[6] Although these values were expected to be much lower than other insulation elements, there is more investigation needed to understand the potential shortcomings of the existing EnergyPlus capabilities for this element. Additional details about this phenomenon are available in the ICF report.

The modeling to simulate a future 100% conversion to electric heat pumps was done to understand how the results may differ if the goal of 100% electrification is achieved. The

Table 7. Impact of Insulation on Total Site Energy Savings by End Use and Climate Zone for the Case with Current Heating Systems Mix (residential)

Climate Zone	Scenario	Total Site Energy Savings [kBtu]
3	Whole Home Insulation Impact	71,468
	Wall Insulation Impact	39,203
	Basement Insulation Impact	6,040
	Attic Insulation Impact	26,927
5	Whole Home Insulation Impact	257,647
	Wall Insulation Impact	137,697
	Basement Insulation Impact	29,940
	Attic Insulation Impact	100,420

Table 8. Impact of Insulation on Total Site Energy Savings by End Use and Climate Zone for the Case with Natural Gas Heating (commercial)

Climate Zone	Scenario	Total Site Energy Savings [kBtu]
3	Whole Office Insulation Impact	472,512
	Wall Insulation Impact	142,056
	Slab Insulation Impact	—
	Roof Insulation Impact	309,987
5	Whole Home Insulation Impact	969,178
	Wall Insulation Impact	327,591
	Slab Insulation Impact	2,594
	Roof Insulation Impact	622,109

Table 9. Embodied Carbon Per Functional Unit of Plastic Insulation Materials

Insulation Material	Embodied Carbon (kg CO_2e/m^2)
XPS	5.63
EPS	3.78
PIR (Wall)	3.49
PIR (Roof)	3.46
cc-SPF	4.21
oc-SPF	1.68
50/50 XPS/EPS	4.71
50/50 cc-SPF/oc-SPF	2.95

Note: cc = closed cell; EPS = expanded polystyrene; oc = open cell; PIR = polyisocyanurate; SPF = spray foam; XPS = extruded polystyrene.

energy savings associated with this assumption can be found in the ICF report.

To determine the embodied carbon of the insulation materials for each of the scenarios, representative emissions values of the materials were used. The representative values include materials that are available today and for the foreseeable future. It is important to note that there are values of materials currently available that were not used due to known material and blowing agent phase out programs.

Embodied carbon values for each of the material types were taken from public sources. Embodied carbon is reported per functional unit as specified in the *UL Product Category Rule for Building Envelope Thermal Insulation Requirements*.[3] In some cases, industry-averaged EPD was used and in some cases, manufacturer-averaged EPD data were used. A summary of the embodied carbon per functional unit used in this study can be found in **Table 9**.

Using the building prototypes, the total embodied carbon investment in the buildings for each of the enclosure elements was calculated. This data were used to calculate the carbon payback and carbon avoidance ratios in the report. The total embodied carbon values are summarized in **Table 10** (residential) and **Table 11** (commercial):

In addition to modeling scenarios that include a 100% conversion to heat pumps, several different future-looking grid scenarios were used to understand the carbon payback and the carbon avoidance ratios associated with the use of plastic insulation materials.

Table 10. Total Embodied Carbon for Different Enclosure Elements Insulation for Climate Zone 3 and Climate Zone 5 (residential)

Scenario	Embodied Carbon [metric tons CO_2e]	
	Climate Zone 3	Climate Zone 5
Wall Insulation	1.74	2.53
Basement Insulation	0.51	1.46
Attic Insulation	3.13	4.11
Whole Home Insulation	5.39	8.09

Table 11. Total Embodied Carbon for Different Enclosure Elements Insulation for Climate Zone 3 and Climate Zone 5 (commercial)

Scenario	Embodied Carbon [metric tons CO_2e]	
	Climate Zone 3	Climate Zone 5
Wall Insulation	15.6	19.6
Slab Insulation	—	1.51
Roof Insulation	25.3	30.4
Whole Office Insulation	40.9	51.5

Table 12. Electricity Emission Rates for Low RE Cost, Medium RE Cost, and High RE Cost

Year	Electricity Emission Rate (kg CO_2e/MWh)		
	Low RE Cost	Medium RE Cost	High RE Cost
2024	327.0	302.7	255.0
2026	342.4	266.7	234.0
2028	330.5	211.6	176.1
2030	324.1	188.7	97.9
2035	325.0	132.1	40.8
2040	313.2	87.8	25.2
2045	315.8	63.7	39.6
2050	282.6	57.6	34.9

Note: RE = renewable energy.

Table 13. Global Warming Potential (GWP) Payback Period Using Different Electricity Rates for Scenario 1: Current Heating Systems Mix (residential)

Scenario	GWP Payback Period [months]					
	Climate Zone 3			Climate Zone 5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	2.8	3.0	3.5	2.2	2.3	2.5
Basement Insulation Impact	5.5	5.9	6.8	6.3	6.5	7.0
Attic Insulation Impact	7.5	8.1	9.3	5.0	5.2	5.6
Whole Home Insulation Impact	4.8	5.2	6.0	3.8	4.0	4.3

Table 14. Global Warming Potential (GWP) Payback Period Using Different Electricity Rates for Scenario 2: 100% Heat Pump Systems (residential)

Scenario	GWP Payback Period [months]					
	Climate Zone 3			Climate Zone 5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	2.7	2.9	3.5	1.4	1.5	1.8
Basement insulation Impact	5.3	5.8	6.8	3.2	3.4	4.1
Attic Insulation Impact	7.4	8.0	9.4	3.0	3.3	3.9
Whole Home Insulation Impact	4.7	5.1	6.1	2.3	2.5	3.0

Table 15. Global Warming Potential (GWP) Payback Period Using Different Electricity Rates for Scenario 1: Current Heating System Mix (commercial)

Scenario	GWP Payback Period [months]					
	Climate Zone 3			Climate Zone 5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	4.9	5.3	6.3	2.8	3.1	3.6
Slab Insulation Impact	—	—	—	72.5	84.6	93.8
Roof Insulation Impact	3.7	4.0	4.8	2.6	2.8	3.2
Whole Office Insulation Impact	3.9	4.2	5.0	2.7	2.9	3.4

Table 16. Global Warming Potential (GWP) Payback Period Using Different Electricity Rates for Scenario 2: 100% Heat Pump Systems (commercial)

Scenario	GWP Payback Period [months]					
	Climate Zone 3			Climate Zone 5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	10.1	10.9	13.0	6.0	6.5	7.7
Slab Insulation Impact	—	—	—	NA*	NA	NA
Roof Insulation Impact	7.5	8.1	9.6	4.4	4.8	5.7
Whole Office Insulation Impact	7.9	8.6	10.2	4.9	5.3	6.3

*NA indicates that negative savings result in infinite payback period. Recall that negative savings were primarily due to the fact that insulation is only applied to the perimeter of the slab in addition to inherent limitations on the F-factor method modeling assumptions.

Table 17. Global Warming Potential (GWP) Avoidance Ratio Using Different Electricity Emissions Rates for Scenario 1: Current Heating Systems Mix (residential)

Scenario	GWP Avoidance Ratio [-]					
	Climate Zone 3			Climate Zone 5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	295	114	84	386	251	229
Basement Insulation Impact	149	59	44	137	94	87
Attic Insulation Impact	109	43	32	171	112	103
Whole Home Insulation Impact	171	67	50	222	146	134

Table 18. Global Warming Potential (GWP) Avoidance Ratio Using Different Electricity Emissions Rates for Scenario 2: 100% Heat Pump Systems (residential)

Scenario	GWP Avoidance Ratio [-]					
	Climate Zone 3			Climate Zone 5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	299	87	52	590	171	103
Basement Insulation Impact	152	44	26	255	74	44
Attic Insulation Impact	110	32	19	270	78	47
Whole Home Insulation Impact	172	50	30	348	101	60

Table 19. Global Warming Potential (GWP) Avoidance Ratio Using Different Electricity Emission Rates for Scenario 1: Current Heating System Mix (commercial)

Scenario	GWP Avoidance Ratio [-]					
	Climate Zone 3			Climate Zone 5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	166	50	31	287	90	58
Slab Insulation Impact	—	—	—	12	8	7
Roof Insulation Impact	218	67	42	319	108	73
Whole Office Insulation Impact	208	63	39	305	100	66

Table 20. Global Warming Potential (GWP) Avoidance Ratio Using Different Electricity Emission Rates for Scenario 2: 100% Heat Pump System Mix (commercial)

Scenario	GWP Avoidance Ratio [-]					
	Climate Zone 3			Climate Zone 5		
	High RE Cost	Med RE Cost	Low RE Cost	High RE Cost	Med RE Cost	Low RE Cost
Wall Insulation Impact	80	23	14	136	39	24
Slab Insulation Impact	—	—	—	NA*	NA	NA
Roof Insulation Impact	109	32	19	183	53	32
Whole Office Insulation Impact	103	30	18	164	48	29

*NA indicates that negative savings result in infinite payback period. Recall that negative savings were primarily due to the fact that insulation is only applied to the perimeter of the slab in addition to inherent limitations on the F-factor method modeling assumptions.

The National Renewable Energy Lab (NREL) Cambium Database low-, medium-, and high-cost predictions of grid conversion to renewable energy for Georgia were selected. Since Cambium only estimates grid emissions rates up to 2050 it was assumed that 2050 rates prevailed for the remainder of the building life-cycle. The emission rates used from the Cambium database are found in **Table 12**.

Utilizing the background data described in the above tables, the GWP payback of plastic insulation materials was calculated assuming current heating system and 100% heat pump scenarios. All insulation elements had a GWP payback under one year except for commercial Climate Zone 3 Low Renewable Energy (RE) Cost of conversion walls with 100% heat pumps and Climate Zone 5 slab insulation scenarios. As described previously, it is suspected to be hampered by the current capabilities of EnergyPlus modeling software. This is the case even if the grid rapidly converts to renewable energy and when 100% of heating systems are converted to heat pumps. Residential wall insulation in Climate Zone 5, assuming 100% heat pump conversion and a High RE Cost of grid conversion, had the most rapid payback at 1.4 months. The carbon payback in months for the residential prototype are found in **Table 13** (current heating system mix) and **Table 14** (100% heat pumps).

The carbon payback in months for the commercial prototype are found in **Table 15** (current heating system mix) and **Table 16** (100% heat pumps).

The lifetime GWP savings and the GWP avoidance ratios attributed to plastic insulation were also calculated. Except for the slab insulation, which is limited by modeling capabilities, it was found that plastic insulation in all other applications had net carbon savings over its useful life. Excepting slab insulation, plastic insulation saves between 14 times and 590 times its embodied carbon during its useful life. The residential GWP avoidance ratios for all scenarios are found in **Table 17** (current heating system mix) and **Table 18** (100% heat pump mix) below.

The GWP avoidance ratios for all commercial scenarios are found in **Table 19** (current heating system mix) and **Table 20** (100% heat pump mix) below.

CONCLUSION

This report concludes that plastic insulation manufacturers, through their own product stewardship and sustainability goals, have made steady improvements to their manufacturing processes and product formulations of plastic insulation materials. These improvements have resulted in significant embodied carbon reductions of insulation materials in the market. Improvements to embodied carbon are likely to continue as production technology improves and the energy sources transition to lower GHG options.

Additionally, the report concludes that the investment of embodied carbon in plastic insulation materials is trumped by its GHG savings benefits during its useful life in buildings. This is true for our current energy grid GHG intensity and the projected grid transition to a cleaner mix even at aggressive conversion speeds. Furthermore, the report shows that the embodied carbon invested in plastic insulation materials has rapid payback times of under one year in nearly all scenarios even when it is assumed that all buildings are converted to heat pump systems.

Outside the building enclosure, insulation also can support global efforts to reach a point of drawdown, where GHGs in the atmosphere stop increasing and decline through many carbon mitigation strategies. This analysis, called Project Drawdown, cites building insulation as one of the climate solutions needed to reach this turning point, further underscoring the benefits of plastic insulation in a low carbon economy.[18] Project drawdown indicates that a steady implementation of low-embodied-carbon insulation materials could lead to more than 15 gigatons of avoided GHG emissions.

Insulation LCA and EPD data should be used in the context of whole building LCA or in combination with total carbon benefit data for insulation materials that includes the use-phase carbon benefits to make smart policy, design, and product selection decisions for the building sector. Evidence shows that including embodied carbon impacts of insulation without considering total carbon analysis would be counterproductive to our global and national carbon reduction goals. Policies, building specifications, industry tools and other resources that include or aim to set maximum embodied carbon limits for insulation or deselect/disincentivize insulation materials based on embodied carbon content alone is misguided and are not recommended in our opinion.

It should be noted that the carbon savings attributed to eliminating the additional air or water resistive barrier were not factored into the carbon savings in this report. These savings can be significant and should be considered by design professionals when making material selections. Furthermore, there can often be cost savings associated when an additional air or water barrier can be eliminated through the sealing of foam insulation. In many cases, the energy savings can lead to the l downsizing of HVAC and renewable energy equipment due to the reduced heating and cooling loads. Further study would need to be done to quantify these benefits.

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