Unlocking Carbon Savings with Plastic Insulation Materials

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ABSTRACT
In recent years, many essential industries including packaging, medical, automotive, and building sectors, have made commitments to improve the sustainability of their products and manufacturing processes. Within each of these essential industries, plastics have played a key role due to plastics' durability and versatility.

Carbon reductions are often included in manufacturer sustainability goals and are a priority for the building sector both globally and domestically. As a result, many manufactures have sought to benchmark their product carbon footprint through life cycle assessments (LCAs). LCAs provide transparency data for producers, brand owners, consumers, and policymakers. This data can be used by producers to help inform product development and improvement decisions, building designers to inform design and product procurement decisions, and policy makers to encourage or mandate change.

The first part of this report highlights improvements in the embodied carbon, calculated as the global warming potential, of the four main plastic insulation types: expanded polystyrene (EPS), extruded polystyrene (XPS), spray foam (SPF), and polyisocyanurate (PIR). A literature review of current and historic environmental product declarations (EPDs) showed that the embodied carbon, expressed as $kgCO_{2eq}$ per functional unit, has significantly decreased for XPS and PIR over several decades. Data was collected from primary sources, including insulation producers, and EPDs certified by a third-party with only U.S. application. The trending downwards of embodied carbon in XPS and PIR can be attributed to reformulations in the blowing agents utilized in both products.

The second part of this report showcases the total carbon benefits of plastic insulation by evaluating savings attributed to insulation materials in residential and commercial building envelopes. The study demonstrates the significant net carbon benefits of insulation including rapid carbon paybacks and significant carbon avoidance ratios. For example, a whole home insulation package has a carbon payback in 2.3 to 6.1 months and a carbon avoidance ratio range of 1:30 to 1:348 depending on heating system and grid factors. A commercial office building insulation package was found to have a carbon payback in 2.7 to 10.2 months and a carbon avoidance ration range of 1:18 to 1:305 depending on heating system and grid factors.

Findings highlight the significant improvements in the embodied carbon of plastic insulation, especially in materials that had historically high Global Warming Potential (GWP), leading to a smaller range of embodied carbon across the four insulation types. The study also shows the significant total carbon benefits of plastic insulation. The carbon invested in the materials (embodied carbon) is paid back many times over soon after a building is put into operation.

INTRODUCTION
Plastic insulation is typically composed of a plastic polymer, such as polyurethanes, 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]

Plastic insulation materials offer value added benefits that many other insulation materials do not. Plastic insulation materials have high thermal resistance (R-value per inch); they're lightweight, durable, and can eliminate the need for additional air and water resistive barriers due to their air and moisture control properties. To date, there has been limited recognition of the unique and beneficial nature of materials like insulation that provide significant carbon benefits during their service life or use phase. Insulation not only provides thermal protection, but also energy and carbon benefits by reducing the heating and cooling loads.

The method of determining the impact of plastic insulation materials is through a Life Cycle Assessment (LCA), which is the quantified analysis of the inventory and impact of a product through the various stages of that product's life. An LCA consists of four stages: 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 (EPDs) that communicates verifiable information. The life cycle of an insulation product includes four stages: product manufacture, building construction, use, and end of life. However, the uses stage does not include avoided carbon only carbon consumption of the material during this phase. The fifth stage, beyond the building's life cycle, addresses the circularity of the insulation product and the benefits of the product experienced indirectly and is often outside the scope of the EPDs. The life cycle phases are divided further into substages called modules shown in Figure 2 module A through module D. Figure 2 depicts the five life cycle phases, modules, and the four types of life cycle scopes: cradle-to-gate, cradle-to-site, cradle-to-grave, and cradle-to-cradle.

EPDs for insulation products examine various impact categories, including the embodied carbon of the insulation material, which is calculated as the global warming potential and expressed as CO_{2eq} or Carbon Dioxide equivalent. This two-part report 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 sides react when combined and is spray applied. PIR or polyiso, is a closed-cell rigid foam board insulation consisting of a foam core typically between two facers. The functional unit for part I and part II of this report is the kilograms (kg) of CO_{2eq}/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. Data was collected from primary sources, EPDs from various PCR years, and peer-reviewed reports. The embodied carbon data was then grouped by their formulation; the most recent formulation of each material from a producer was used for part II of the report.

Figure 1. Displays the modules for each life cycle stage of the insulation.

<table>
<tr><th colspan="7">Building Life Cycle Stages</th></tr>
<tr><td rowspan="3">Product</td><td>A1</td><td>Raw material extraction</td><td rowspan="3">Cradle-to-Gate</td><td rowspan="5">Cradle-to-Site</td><td rowspan="16">Cradle-to-Grave</td><td rowspan="17">Cradle-to-Cradle</td></tr>
<tr><td>A2</td><td>Transport</td></tr>
<tr><td>A3</td><td>Manufacturing</td></tr>
<tr><td rowspan="2">Construction</td><td>A4</td><td>Transport</td></tr>
<tr><td>A5</td><td>Construction / Installation</td></tr>
<tr><td rowspan="7">Use</td><td>B1</td><td>Use</td></tr>
<tr><td>B2</td><td>Maintenance</td></tr>
<tr><td>B3</td><td>Repair</td></tr>
<tr><td>B4</td><td>Replacement</td></tr>
<tr><td>B5</td><td>Refurbishment</td></tr>
<tr><td>B6</td><td>Operational energy use</td></tr>
<tr><td>B7</td><td>Operational water use</td></tr>
<tr><td rowspan="4">End of Life</td><td>C1</td><td>Deconstruction</td></tr>
<tr><td>C2</td><td>Transport</td></tr>
<tr><td>C3</td><td>Waste processing</td></tr>
<tr><td>C4</td><td>Disposal</td></tr>
<tr><td>Beyond Building Life Cycle</td><td>D</td><td>Reuse/ Recover/ Recycling</td></tr>
</table>

Outside of boundary scope

Over the last several decades, plastic insulation has included blowing agents from CFCs, to HCFCs, to HFCs, and HFOs. Part I of the "Results and Discussion" section describes the shift from more carbon-intensive blowing agents to those with a lesser carbon footprint. The decreasing footprint 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 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 carbon-related policy and develop solutions surrounding decisions on the sustainability of plastic insulation. Additionally, there is insufficient data on the total carbon impacts of insulation, including the embodied carbon of insulation material and the carbon benefits of these materials. Therefore, this two-part report aims to A) highlight the historical reductions in the embodied carbon (calculated as GWP) 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 envelopes.

EXPERIMENTAL

PART I

The carbon footprint of each insulation type is determined by calculating the potential carbon impacts of the insulation products in accordance with the Product Category Rule (PCR) Guidance, Building Envelope Thermal Insulation EPD Requirements UL 10010-1. The PCR includes stages A1-A5, B1-5, and C1-C4. Impacts of other stages 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 environmental impacts are included in a product's EPD, this report focuses on greenhouse gas emissions (GHGs). GHGs are gases that absorb and trap heat in the atmosphere; the most common GHGs include Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (NO_x). 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 varying 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. GWP is measured as kilograms (kg) of CO_2 equivalent and allows different GHGs to be compared on the same scale.

To compare the changes in the GWP of the four plastic insulation types, data was collected from primary sources through a survey where producers were requested to provide current and historical embodied carbon metrics along with the PCR year and include any notable changes that may have caused the change in embodied carbon from one PCR to the next. Additional data was collected from industry and producer EPDs available on the EC3 database. Data from peer-reviewed sources was 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 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.[2] The model results were compared to the embodied carbon investment materials in prototype buildings so that an understanding of carbon payback and carbon avoidance (embodied carbon to carbon savings) could be established.

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 timeframes.[3] While this study used different modeling assumptions than the recent ICF study and was conducted nearly two decades prior, the results reiterated the benefit of plastic insulation applications. Furthermore, these results were positive despite the higher embodied carbon of insulation materials at that time. The Franklin study showed that by adding an additional 5/8" 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 U.S. to 3 years in Canada could be achieved.

Another research report in the Journal of Industrial Ecology (JIE), "Life Cyle Greenhouse Gas Emissions Reduction from Rigid Thermal Insulation Use in Buildings was published in 2011," found an average emissions savings to embodied emissions ratio of 48:1.[4] As with the Franklin study, this study used different modeling assumptions than the ICF study but found similarly significant total carbon benefits of plastic insulation materials when considering the useful life benefits. It's important to note the emissions data per functional unit in the 2011 study was not subjected to the same third-party analysis or Product Category Rules (PCR) as with the ICF study.

There are a handful of other industry wide and manufacturer specific studies 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, while based on historical examples of total carbon studies, 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 residential two-story home and medium office building prototypes. ICF utilized DOE's Energy Plus software to model the energy data. ICF also calculated the total embodied carbon of the insulation materials in the modeled buildings and used current and projected grid data to determine the total carbon impacts. Using the data, ICF calculated the plastic insulation material carbon payback and carbon avoidance ratios using Cambium High, Medium, and Low Cost of Conversion to Renewable Energy grid projections. The data was then compared to the embodied carbon investment in these materials in prototype buildings so that an understanding of carbon payback and carbon avoidance could be established.

Climate zones 3 and 5 were selected to include zones that were conservatively representative of heating and a cooling dominated regions of the U.S. See Table 1 below. 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 U.S. Census Bureau Building Permits Survey.[5]

Figure 2. depicts the International Energy Conservation Code (IECC) map dividing the United States into eight temperature climate zones. Each zone is divided further into three moisture regions denoted by A, B, and C.[6]

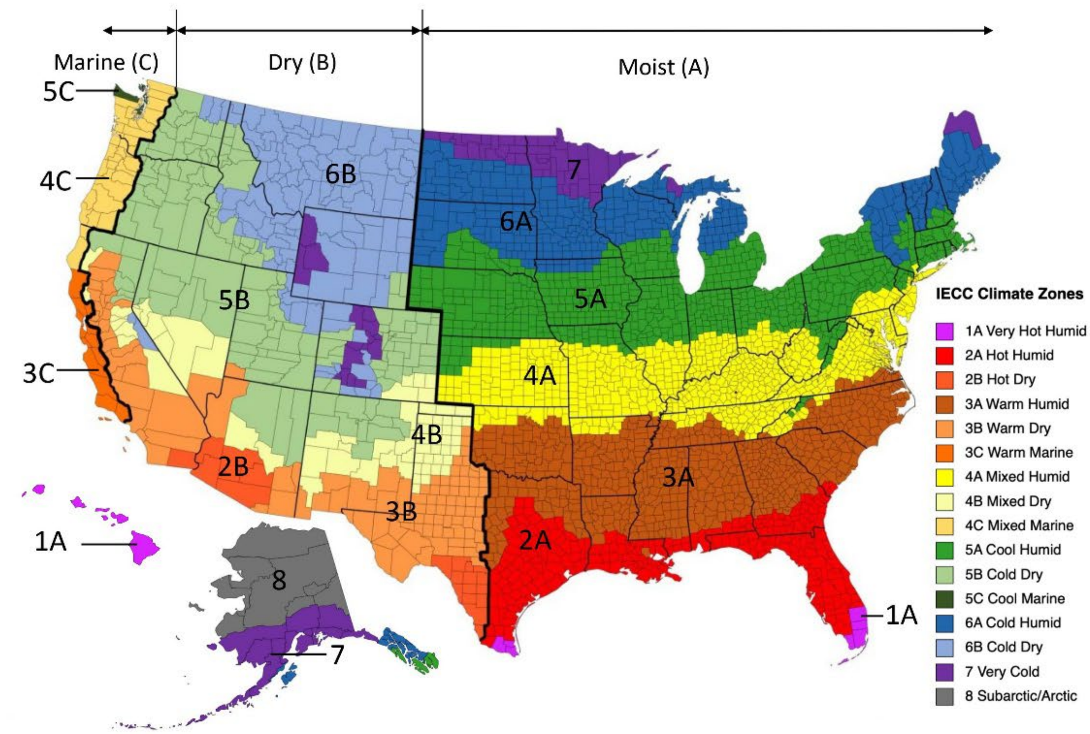


Table 1. Representative Climate Zones 3 and 5 Modeling Assumptions

Climate Zone	Representative City	Weather Location	HDD65	CDD65
CZ3A	Atlanta, Georgia	Atlanta/Hartsfield Jackson International Airport, Georgia	2,498	2,099
CZ3B	El Paso, Texas	El Paso International Airport, Texas	2,012	2,972
CZ3C	San Diego, California	San Diego/Brown Field Municipal Airport, California	1,377	763
CZ5A	Buffalo, New York	Buffalo Niagara International Airport, New York	6,242	769
CZ5B	Denver, Colorado	Denver/Aurora/Buckley AFB, Colorado	5,737	832
CZ5C	Port Angeles, Washington	Port Angeles/William R Fairchild International Airport, Washington	5,488	20

Representative thermo-physical properties were established. See Table 2 below. These values do not reflect all available or proprietary insulation properties. They are conservative representations of materials readily available in the U.S.

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/ft^3 (kg/m^3)	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)

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 2-story home. This is typically more conservative than the 1-story home prototype due to its smaller footprint 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 others larger more energy intensive buildings like schools and hospitals.

Four base modeling scenarios were developed for residential, and four modeling scenarios were developed for commercial. These scenarios simulated the buildings without insulation (R0/C0), the buildings without wall insulation (R1/C1), the buildings without basement/slab insulation (R2/C2), the buildings without attic/roof insulation (R3/C3), and the buildings fully insulated (R4/C4). See Tables 3 and 4 below.

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

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 averaged (50/50 blend). The representative insulation types selected are shown in Table 5 for residential and 6 for commercial. For residential the configurations for both the insulation at 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.

Table 5. 2021 IECC Minimum Insulation R-values and Envelope Components

Location	Climate Zone	
	CZ 3	**CZ 5**
Above-Grade Exterior Wall Insulation	R-13 oc-SPF/cc-SPF blend 50/50 in cavity, R-5 continuous insulation (ci) 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 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 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

Table 6. ASHRAE 90.1-2019 Minimum Insulation R-values and Envelope Components

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

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

A few changes were made to the EnergyPlus model to better represent the configuration of envelope 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.

A 75-year useful life assumption was used. This is the same useful life assumption in the Product Category Rule used for the development of Life Cycle Analysis for thermal insulation materials used to determine their embodied carbon.

There was a total of 147 simulations modeled, 120 for residential and 27 for commercial. There were more simulations run for residential mainly 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.

RESULTS and DISUCSSION

PART I

While there are many factors that have lead to reductions in the embodied carbon of insulation products, blowing agents have presenting 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.[7] CFCs were utilized as blowing agents in foam insulation materials where they formed air-filled pockets creating a barrier restricting heat transfer and reducing 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 carbon footprint demonstrated by their high GWP due to their ability to trap more heat compared to other greenhouse gases, including Carbon Dioxide. According to a study on the greenhouse gas emission 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_{2eq}/m^2.[3]

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.[8] 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, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (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_{2eq}/m^2. However, HCFCs were shown to have similar potential to CFCs to deplete the ozone layer prompting an amendment to the Montreal Protocol outlining their planned phase out as well. This precipitated the substitution of HCFCs with HFCs. While HFCs do not have ozone depleting properties, they have significant carbon footprints 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.[9] These substances will be replaced by lower GWP blowing agents, such as Hydrofluoroolefins (HFOs) or pentanes.

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

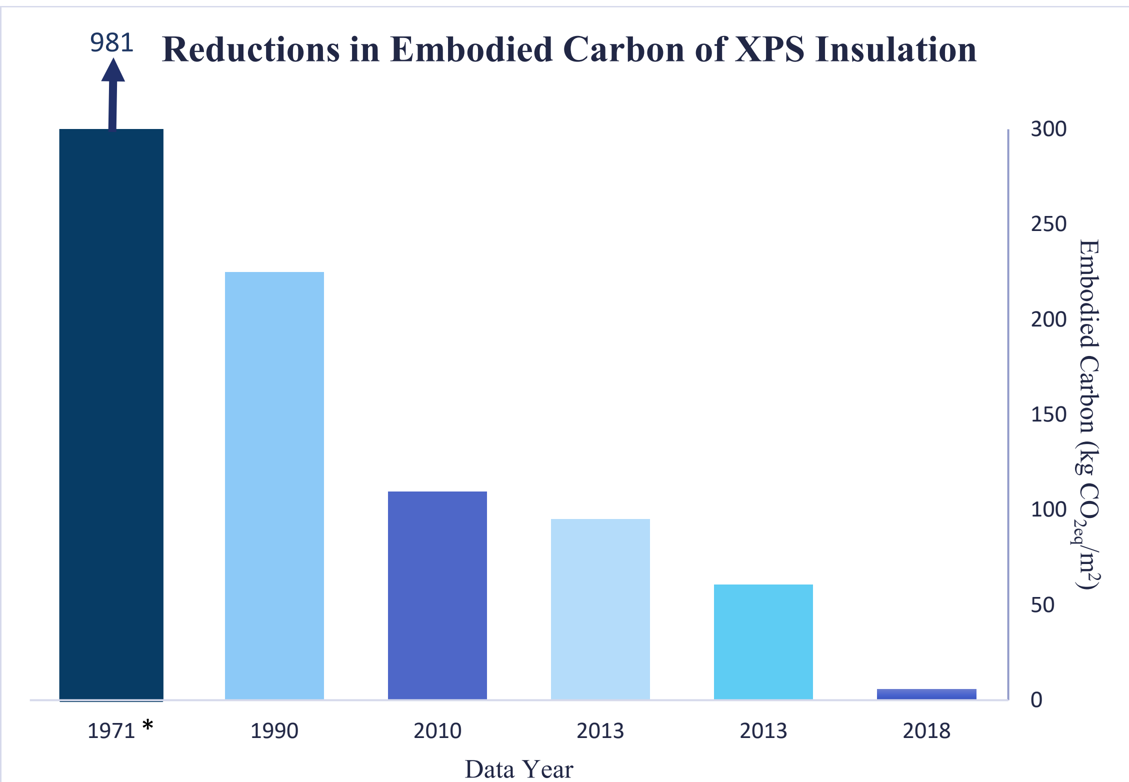
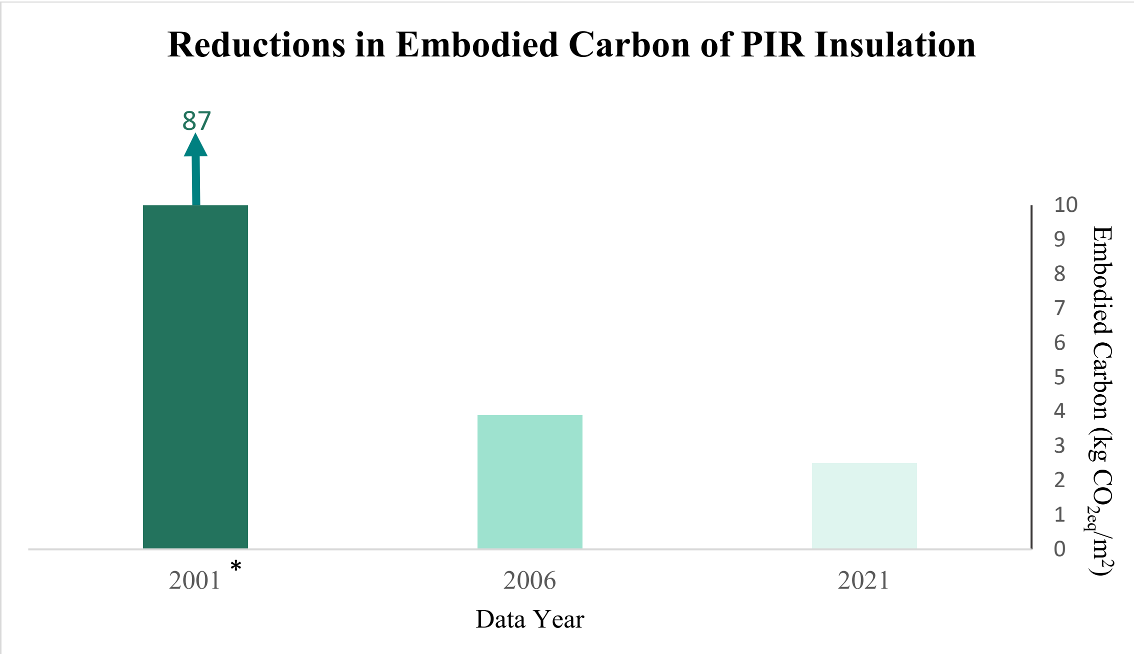


Figure 3 showcases the reductions in embodied carbon of XPS insulation materials over the last several decades. The years indicated on the X-axis correlate to the year a new generation of XPS was introduced. The embodied carbon of XPS has been significantly reduced since 1971, primarily as a result of 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 towards 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.

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



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 Europe will have varying results compared to plastic insulation materials produced in the United States, especially given the differences in fuel mixes. Furthermore, expired EPDs are removed from databases and other building resources to ensure that only current data on the contents and footprint of plastic insulation materials are communicated. While beneficial in reducing the communication of outdated metrics, this presents as a challenge in collecting historical information. Additionally, the tracking of plastic insulation's carbon footprint 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 carbon footprints throughout their lifecycles.

PART II

<u>Determination of Total Carbon Impacts</u>

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 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. From this consumption data the energy savings of the insulation elements associated with each scenario was determined and summarized in Tables 7 (residential) and 8 (commercial) as shown below.

The IC report noted, consistent with anomalies experienced with EnergyPlus, that the software seems to undervalue slab insulation contributions. 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.

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)

CZ	Scenario	Total Site Energy Savings [kBtu]
CZ3	Whole Home Insulation Impact	71,468
	Wall Insulation Impact	39,203
	Basement Insulation Impact	6,040
	Attic Insulation Impact	26,927
CZ5	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)

CZ	Scenario	Total Site Energy Savings [kBtu]
CZ3	Whole Office Insulation Impact	472,512
	Wall Insulation Impact	142,056
	Slab Insulation Impact	-
	Roof Insulation Impact	309,987
CZ5	Whole Home Insulation Impact	969,178
	Wall Insulation Impact	327,591
	Slab Insulation Impact	2,594
	Roof Insulation Impact	622,109

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 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. In some cases, industry averaged Environmental Product Data (EPD) was used and in some cases, manufacturer averaged EPD data was used. A summary of the embodied carbon per functional unit used in this study can be found in Table 9 below.

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
Polyisocyanurate (Wall)	3.49
Polyisocyanurate (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

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

Table 10. Total Embodied Carbon for Different Envelope Elements Insulation for CZ3 and CZ5 (residential)

Scenario	Embodied Carbon [metric tons]	
	CZ3	CZ5
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 Envelope Elements Insulation for CZ3 and CZ5 (commercial)

Scenario	Embodied Carbon [metric tons]	
	CZ3	**CZ5**
Wall Insulation	15.6	19.6
Slab Insulation	-	1.51
Roof Insulation	25.3	30.4
Whole Office Insulation	40.9	51.5

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. 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 below.

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

Utilizing the background data described in the above Tables, the carbon payback of plastic insulation materials was calculated assuming current heating system and 100% heat pump scenarios. All insulation elements had a carbon payback under one year except for commercial climate zone 3 Low RE Cost of conversion walls with 100% heat pumps and climate zone 5 slab insulation scenarios. As described above, 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 Tables 13 (current heating system mix) and 14 (100% heat pumps).

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

Scenario	Carbon Payback Period [months]					
	CZ3			CZ5		
	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. Carbon Payback Period Using Different Electricity Rates for Scenario 2: 100% Heat Pump Systems (residential)

Scenario	Carbon Payback Period [months]					
	CZ3			CZ5		
	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

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

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

Scenario	Carbon Payback Period [months]					
	CZ3			CZ5		
	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. Carbon Payback Period Using Different Electricity Rates for Scenario 2: 100% Heat Pump Systems (commercial)

Scenario	Carbon Payback Period [months]					
	CZ3			CZ5		
	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.

The lifetime carbon savings and the carbon 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 carbon avoidance ratios for all scenarios are found in Tables 17 (current heating system mix) and 18 (100% heat pump mix) below.

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

Scenario	Carbon Avoidance Ratio [-]					
	CZ3			CZ5		
	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. Carbon Avoidance Ratio Using Different Electricity Emissions Rates for Scenario 2: 100% Heat Pump Systems (residential)

Scenario	Carbon Avoidance Ratio [-]					
	CZ3			CZ5		
	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

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

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

Scenario	Carbon Avoidance Ratio [-]					
	CZ3			CZ5		
	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. Carbon Avoidance Ratio Using Different Electricity Emission Rates for Scenario 2: 100% Heat Pump System Mix (commercial)

Scenario	Carbon Avoidance Ratio [-]					
	CZ3			CZ5		
	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.

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 carbon options.

Additionally, the report concludes that the investment of embodied carbon in plastic insulation materials is trumped by its carbon savings benefits during its useful life in buildings. This is true for our current energy grid carbon intensity and the projected grid transition to a cleaner mix even at aggressive conversion speeds. Furthermore, the report shows that the 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 envelope, insulation also has the potential to support global efforts to reach a point of drawdown, where greenhouses gases in the atmosphere stop increasing and begin to decline through a multitude of 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. Project drawdown indicates that a steady implementation of low-carbon insulation materials could lead to more than 15 gigatons of avoided emissions.

This demonstrates that insulation LCA and EPD data should be used in the context of Whole Building Life Cycle Analysis 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.

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, the cost savings of eliminating the air and water resistive barrier in addition to the potential downsizing of HVAC and renewable energy equipment due to the reduced heating and cooling loads attributed to a well-insulated and air sealed building envelope should be factored into design decision making. Further study would need to be done to quantify these benefits.

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