STP 1657 On *The Changing Face of Building Materials and Systems in Response to Climate Change*

Review and Assessment: The Role of Foam Plastic Insulation in Mitigating and Adapting to Climate Change

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ABSTRACT

Building systems and materials are being called upon today to provide greater levels of performance in many areas. Resilience is needed to protect against severe weather due to climate change, especially as the population in urban and coastal regions increases. Embodied and operational carbon emissions reductions also are needed to help stop or at least slow down climate change and its expected impacts. Affordability, energy efficiency, labor efficiency, and other concerns cannot be ignored. These challenges require a holistic approach to optimization so that improving one performance metric does not fundamentally harm another, particularly when including carbon emission mitigation as an additional design optimization consideration. A "total carbon" (whole-building life cycle) approach is needed to effectively minimize climate change impacts. This paper assesses the role of foam plastic insulation materials (and insulation materials in general) as a means to optimize building systems for the purpose of climate change mitigation and resilient adaptation. The paper traverses the following topics from a data-driven perspective to better inform design and policy decisions for building decarbonization: (1) building materials and their contributions to global and U.S. greenhouse gas (GHG) emissions; (2) contribution of insulation embodied carbon to global and U.S. GHG emissions; (3) advancements in foam plastic insulation materials to lower their global warming potential (GWP) and maintain critical performance characteristics; (4) operational emissions savings (carbon payback and carbon avoidance) of building insulation in light of building electrification, a changing power grid, and the importance of building envelope efficiency; and (5) multifunctional applications of foam plastic insulation to optimize building system design, performance, resiliency, resource efficiency, affordability, and total carbon reductions in the construction and operation of buildings.

Keywords

climate, insulation, construction, building, envelope, carbon, emissions, efficiency, resilience, durability

Introduction

There is unequivocal agreement among the scientific community that humans have a shrinking global greenhouse gas (GHG) emissions budget to avoid an unacceptable global temperature rise.[1–5] The planet is warming, and as a result we are experiencing changes in agriculture, availability of water, sea levels, and weather. These present and future impacts can be monetized as the social cost of carbon with a present value estimate of about $200 per metric ton of CO_2e emissions.[6] Consequently, these realities demand sensible and coordinated action toward the decarbonization of all sectors of the economy,[4] including buildings.[7,8] For a thorough review of climate science, policies, relevant data, and recommended actions for buildings and building materials, see the 2023 study by the Applied Building Technology Group.[9] The remainder of this paper focuses on the crucial role of building insulation materials as part of an effective building decarbonization pathway.

The building energy codes in the United States are based on eight climate zones that dictate how builders insulate and condition homes and buildings for human occupancy, productivity, comfort, and protection. As these climate zones continue to warm and shift due to climate change, policymakers must continue to cost-effectively add more protection against the extreme weather events that are having an increasing effect on large portions of the population, including urban and coastal regions. This added resilience may come through a combination of coordinated changes in energy codes, building codes, and other programs or regulations.

Codes, standards, programs, and regulations are now attempting to address GHG emissions as the root cause of climate change. But this is a relatively new area of building science, with evolving data, methodologies, and criteria. In the rush to cut our emissions, aggressive goals are being set to achieve net zero emissions by 2050 or sooner. But practically meeting those goals is not easy and may necessitate establishing priorities to focus on efforts with the greatest return on investment. Current building practices are far from achieving net zero emissions, and the existing building stock is even further behind.

Two emission reduction paths need to converge. The most important and significant path addresses the attainment of net zero operational emissions for buildings. A secondary concern with smaller climate benefits relates to the reduction of the embodied carbon emissions attributed to building materials, particularly insulation. Success will require nearly 100% global compliance, a clean electric grid, and an effective transition to clean electric or other renewable heating energy sources for buildings and industries on site. While this goal is daunting, the nation should sensibly strive to do what it can while it also puts in place additional building resilience so that our buildings can better adapt to the climate changes the planet will continue to experience.

Insulation had been part of the solution before the problem was identified. For more than 50 years, insulation manufacturers have been working to lower their products' embodied carbon,[10] reduce building operational energy needs, make buildings more resilient by providing passive thermal survivability,[11] and lower utility bills. Their work is ongoing, and this paper presents a snapshot of the progress and key findings to date.

CONTRIBUTIONS OF BUILDING MATERIALS TO GHG EMISSIONS

The industry is far from understanding how many building materials contribute to GHG emissions and is just beginning to understand a few broad material categories: concrete, gypsum boards and panels, steel, insulation, and glass. Much of the reason is that these industries supply transparency information such as environmental product declarations (EPDs) only on a voluntary basis. A bill of materials list for any building is going to include many more materials for which we still do not have good data on embodied carbon. This is especially true for products that have multiple parts and pieces, such as window assemblies, HVAC equipment, solar panels, and other materials with complicated supply chains.

Even for the materials that have the most transparency data, it is difficult to assign individual global contributions because of differences in carbon accounting and reporting. These differences include different product category rules (PCRs), differences in life cycle assessment (LCA) tools, and differences in human judgment regarding inputs. However, according to the United Nations Environment Programme,[12] it is estimated that building materials as a whole account for 10% of global GHG emissions.

In the United States, our understanding of the aforementioned building materials is improving. Table 1 shows current data from a review of the best available sources as noted in the table. These data show that the embodied carbon of U.S. building materials (excluding non-building-related infrastructure applications) is responsible for about 0.4% of annual global GHG emissions, or about 4% of annual U.S. GHG emissions. While these contributions are notably low in comparison to the global scale of GHG emissions, opportunities to further reduce our emissions remain, and all viable solutions should continue to be explored.

TABLE 1 Greenhouse gas emissions for world, United States, U.S. economic sectors, and U.S. building and construction materials, 2020

Source	**Gross GHG Emissions, $GtCO_2e$[a]**	**% of Total Global GHG Emissions**	**% of Total U.S. GHG Emissions**	**% of Total U.S. Bldg & Const Mat'l Emissions**
Global total (~80% FFC)[b]	59	100%		
U.S. total (~73% FFC)[b]	6.0	10.1%	100%	
GHG Emissions by U.S. Economic Sectors				
Transportation	1.63	2.8%	27%	
Electric power	1.48	2.5%	25%	
Industry[c]	1.43	2.4%	24%	
Buildings	0.79	1.3%	13%	
Agriculture	0.64	1.1%	11%	
GHG Emissions by U.S. Building and Construction Materials[d]				
Concrete	0.100	0.17%	1.7%	28%
Gypsum board and panels	0.080	0.14%	1.3%	22%
Steel (structural)	0.052	0.09%	0.9%	13%
Building insulation (all types)	0.006	0.01%	0.10%	1.7%
Flat glass for glazing	0.005	0.008%	0.08%	1.4%

All others (unquantified)	0.12	0.2%	2.0%	34%
Total bldg & const mat'ls Total bldg mat'ls only	0.36 0.24	0.61% 0.41%	6% 4%	100% 68%

Sources: Data gathered from various studies,[2–4,8,13] as documented by the Applied Building Technology Group.[9]

[a]1 $GtCO_2e$ = 1 billion metric tons of CO_2e = 1 trillion kg of CO_2e emissions (equivalent to CO_2 emissions from combustion of about 110 billion gallons of gasoline); data in table based on gross emissions, excluding carbon sinks.

[b]FFC = fossil fuel combustion.

[c]About 25% of industry emissions (1.43 $GtCO_2e$) are associated with emissions that are attributed downstream to building and construction materials as embodied emissions (0.36 $GtCO_2e$).

[d]Embodied emissions, a subset of industry emissions.

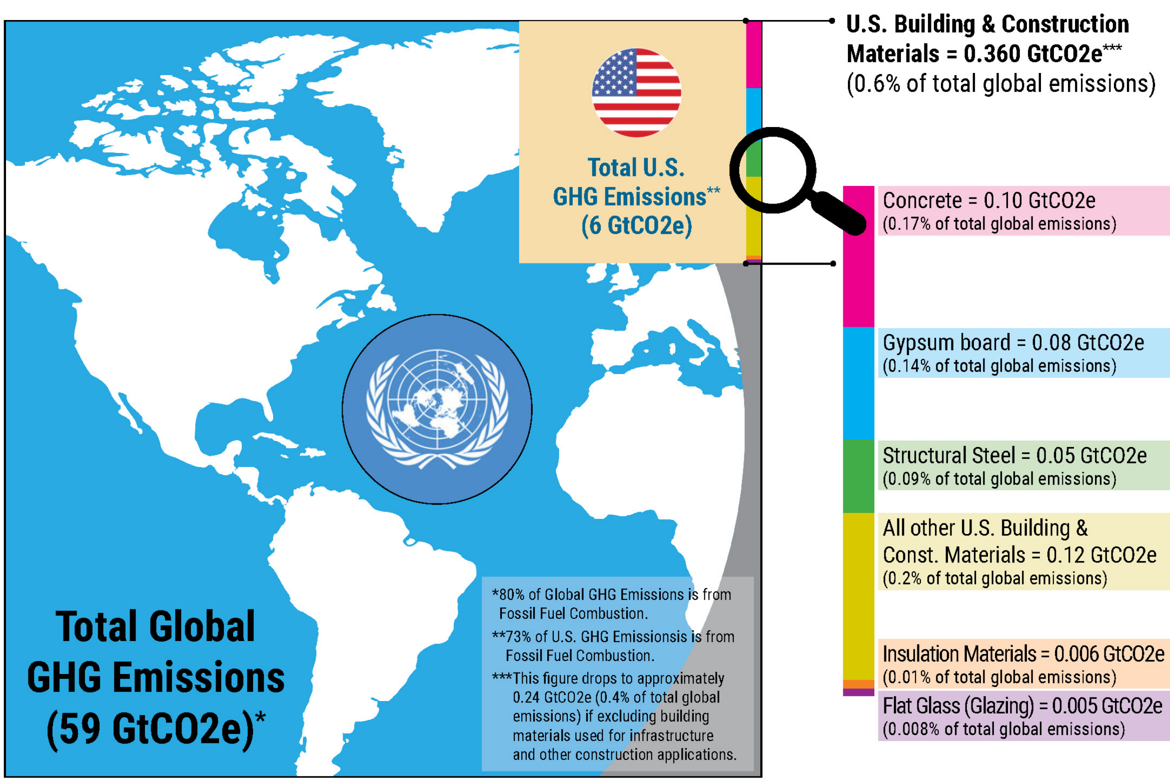
INSULATION CONTRIBUTIONS TO EMISSIONS

Insulation manufacturers were among the first to provide transparency information to the industry in the form of EPDs. This was largely in response to requests from the architectural community for information about material composition. Over time attention largely shifted to the carbon emissions data reported in their EPDs.

As shown in table 1, the embodied carbon attributed to building insulation manufactured in the United States in a given year only makes up about 0.10% of annual U.S. GHG emissions (or about 0.01% of annual global GHG emissions). This contribution is more than an order of magnitude less than structural materials like concrete and steel or gypsum board products. While the embodied carbon contributions of insulation are relatively small, the availability of insulation embodied carbon data has made insulation an easy target for designers and regulators to include in policies aimed at limiting embodied carbon.

Again, the reality of these very small numbers is not presented to encourage inaction. However, it is important to understand where emissions are coming from and their significance to global climate change if we want to prioritize our investments in reducing carbon emissions globally and particularly in the United States. Figure 1 provides a graphical representation of the data in table 1 and makes it easier to visualize the contributions of U.S. building and construction materials. As noted in the figure, fossil fuel combustion is responsible for the majority of GHG emissions. In fact, 80% of global and 73% of U.S. GHG emissions come from fossil fuel combustion, not its use as raw material feedstock for the manufacturing of beneficial materials like plastics.

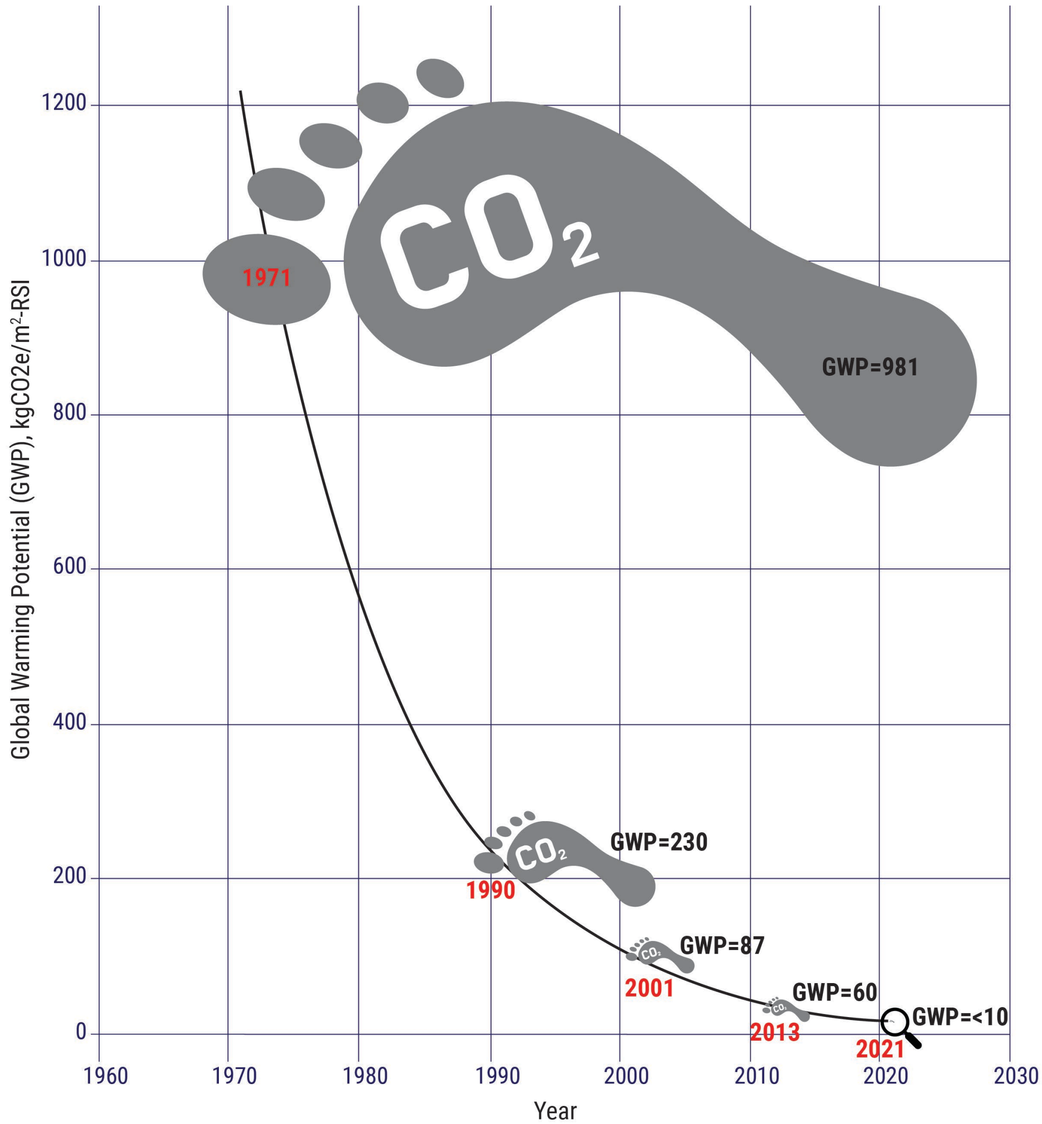
FIG. 1 Magnitude of total global and U.S. GHG emissions and contributions of U.S. building and construction materials to global GHG emissions. Adapted from 2024 Applied Building Technology Group study.[14]



ADVANCEMENTS IN GLOBAL WARMING POTENTIAL (GWP) OF FOAM PLASTIC INSULATION

Not all foam plastic insulation materials are alike. They vary in composition, application, performance, and other factors. Historically some types of foam plastic insulation also had inherently higher embodied carbon or carbon footprint impacts than others. That is no longer the case. Foam plastic insulation manufacturers have made tremendous investments and strides in lowering the GHG emissions of their materials. For example, in the 1970s, extruded polystyrene (XPS) had the highest embodied carbon footprint of all foam plastic insulations: 981 kg CO_2e/m^2-RSI. But XPS and other foam plastic insulation manufacturers have made steady improvements in product composition and manufacturing processes that have resulted in a huge drop in embodied carbon, as shown in figure 2.

FIG. 2 Improvements in embodied carbon footprint of foam plastic insulating sheathing materials (1970 to present). Adapted from 2024 Applied Building Technology Group study.[14]



Today, nearly all U.S.-manufactured insulation materials have an embodied carbon footprint of less than 10 kg CO_2e/m^2-RSI. Some foam plastics have experienced a reduction in GWP of as much as three orders of magnitude over the past several decades because of innovations that have continued to the present. This fact is unknown to many practitioners and policymakers, and it is hard to blame them. The web and some current tools or databases still recognize embodied carbon data for products that are no longer in the market because they have been replaced by low-GWP materials. For example, the EC3 database continues to include EPDs and data for XPS insulation that has a GWP of 20–76 kg CO_2e when none of these materials are being manufactured in the United States or Canada today.

Foam plastic insulation manufacturers have been able to make improvements and maintain other critical performance criteria that are necessary or sought after for various building envelope design applications (e.g., high R-value per inch, air and vapor control properties, compressive strength, and moisture resistance).

But the embodied carbon "footprint" of insulation only tells a very small part of its impact story. To understand the total carbon impact of insulation (insulation's handprint) one also needs to look at the emissions savings that result from its use over the course of a building's operational life.

THE IMPACT OF INSULATION ON EMISSIONS SAVINGS

Insulation and air-sealing materials are among the very few materials that passively save carbon during their useful life. Materials such as these require a total carbon or handprint approach to carbon accounting. Looking only at their embodied carbon fails to take into consideration the overwhelming benefits of their use.

Several studies have now been conducted to quantify the total carbon savings or handprint of insulation materials.[9] All of them, old and new, tend to conclude that insulation materials save more carbon during their service life than is invested in their manufacture. To put it another way, the operational carbon savings attributed to the use of insulation completely overshadow the embodied carbon of a building envelope's insulation materials.

The most recent study by ICF[15] shows that, based on current GWP data for plastic insulation materials in typical prototype buildings in Climate Zone 5, there is a carbon payback of 2.7 to 10.2 months for a commercial office building and a payback of 2.3 to 6.1 months in a typical home. A similar study done in 2011 was published in the *Journal of Industrial Ecology*.[16] This study showed that using XPS even at its previously higher GWP values produced a net average carbon savings to emissions ratio of 48:1. And in 2000, Franklin Associates studied the GHG savings associated with the use of foam sheathing insulation in single-family homes in North America.[17] They found that the payback was 12.5 years for GHG emissions using even older formulations with higher GWP and a shorter operational service life. Finally, a study dating back to the 1990s understood and similarly documented the importance of a total carbon approach to building insulation materials.[18]

As shown in figure 3, recent studies, taking into account the GWP (embodied carbon) of modern foam plastic insulation materials and future grid scenarios as projected by the National Renewable Energy Lab (NREL) Cambium tool, demonstrate that the average net carbon savings or handprint of the building envelope insulation package typically exceeds the small initial embodied carbon footprint by two orders of magnitude (100×) or more over a 60-year service life. NREL's Cambium datasets model hourly emission, cost, and operational data for projected future energy grid scenarios. The scenarios used for the ICF research[15] simulate high cost/slower speed, medium cost/medium speed, and low cost/fast speed of clean grid transition. Figure 3 is based on a typical residential building in Climate Zone 5 using a moderate- to high-efficiency gas furnace for heating. The analysis compares a Department of Energy single-family prototype home with no insulation to a home with 2021 International Energy Conservation Code insulation levels. The total embodied carbon contribution of the materials and operational carbon savings attributed to the full package of specified insulation materials was calculated to characterize the insulation packages' carbon impact on the building. The actual carbon handprint will vary based on climate, energy source for heating, electric grid region, building occupancy type, and other factors. For example, a sensitivity analysis included in the framework of the ICF study[15] demonstrated that the carbon avoidance ratio (ratio of carbon-savings handprint to carbon-investment footprint) may range from about 20 to as much as 400, with lower values occurring in the cleaner electric grid regions and for buildings with higher-efficiency electrified heating systems. While the carbon-savings benefits varied significantly, they were all found to be substantially positive.

FIG. 3 Net carbon savings (handprint) of foam plastic insulation over 60 years. Adapted from 2024 Applied Building Technology Group study.[14]

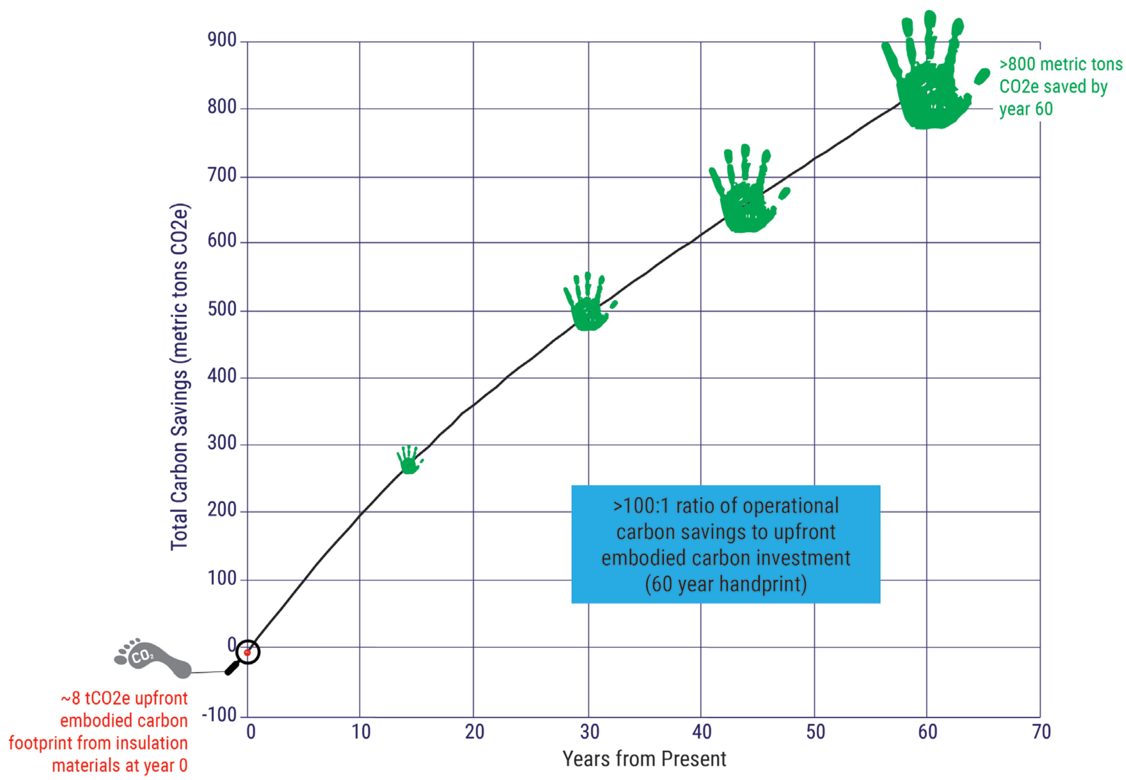
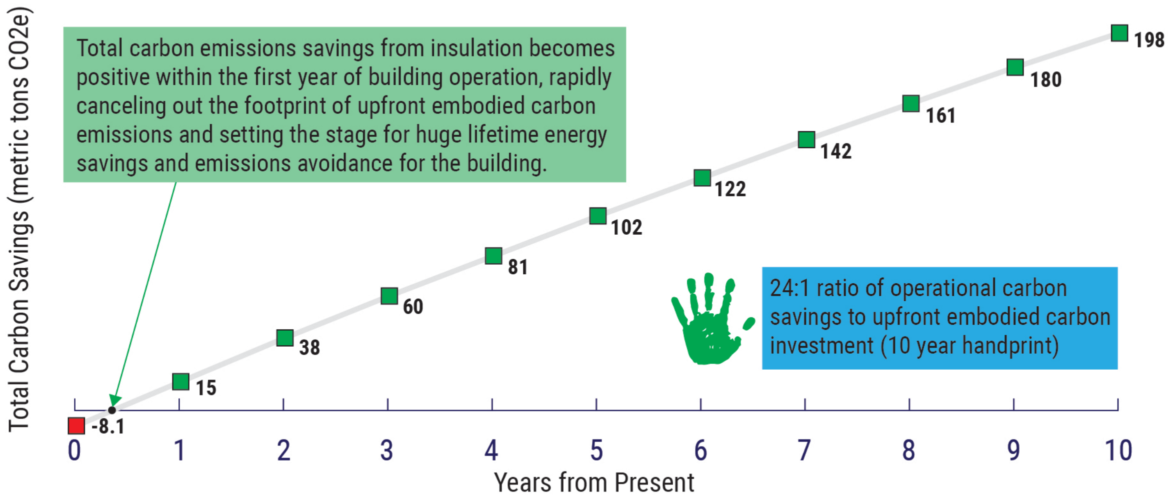


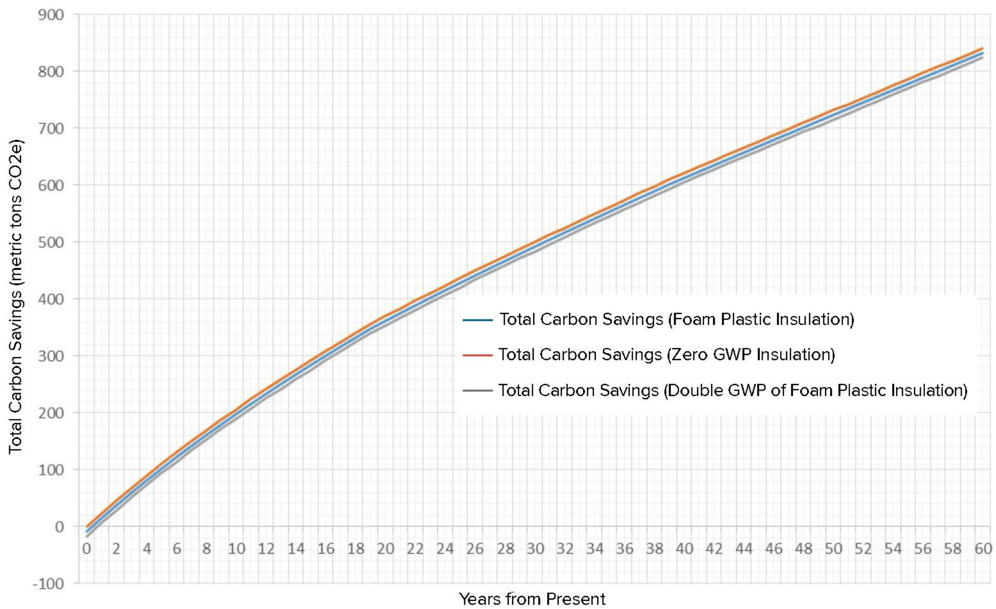
Figure 4 provides a closeup of figure 3 showing the point at which the net carbon savings becomes positive (payback period). The payback period occurs within the first year of building operations, setting the stage for a lifetime of emissions saving. The carbon savings to investment ratio for the first 10 years of the building's life is 24:1, producing rapid climate mitigation benefits.

FIG. 4 Carbon emissions break-even point (less than 1 year) and 10-year savings ratio. Adapted from 2024 Applied Building Technology Group study.[14]



Further analysis in figure 5 shows that even if the embodied carbon of insulation materials were zero or double what it is today, the total carbon savings or handprint of insulation would be tremendous and essentially unaffected by a range of differences in the embodied carbon of modern insulation materials. The consistency and significance of these data are compelling and should be regarded when contemplating carbon policies for insulation materials and efficiency policies for building envelopes. The data also demonstrate that energy efficiency and operational carbon savings should be the focus of building decarbonization when using modern insulation materials, including foam plastics.

FIG. 5 Total carbon savings (handprint) comparison of current, zero, and double GWP insulation materials over 60 years. Adapted from 2024 Applied Building Technology Group study.[14]



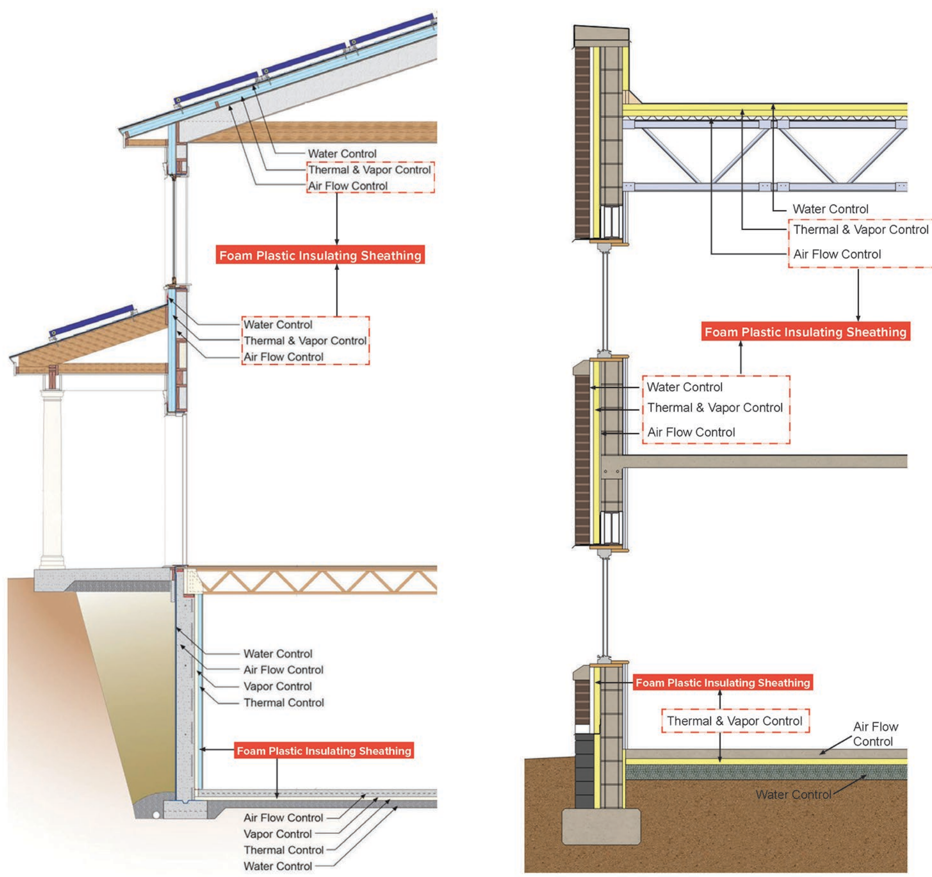
OPTIMIZING BUILDING DESIGN AND PERFORMANCE

Foam plastic insulation, like insulated foam sheathing, serves many purposes beyond its obvious insulating capabilities that result in energy and carbon savings. It can serve as an air- and water-resistive barrier, control condensation, protect foundations from frost, and improve passive thermal survivability.

These compounding benefits have not been included in the carbon savings analysis done to date. But factoring these additional functions into a whole-building LCA could result in even greater carbon savings for foam plastic insulated sheathing and other similar multifunctional insulation materials. When used as an air- or water-resistive barrier, for example, this insulation can eliminate the need for a separate weather barrier, reducing the building's overall embodied carbon. Likewise, when used in frost-protected shallow foundations (FPSF), it eliminates the need for deeper footings and thus reduces the amount of concrete required, thereby saving costs, materials, energy, and embodied carbon. For a typical-size home with an FPSF, the net embodied carbon savings from reduced concrete usage can approach several metric tons of emissions, as occurred in an efficiently designed production home including other cost-saving and performance features.[19] These optimized savings would be increased for commercial and residential buildings with a larger foundation perimeter.

As shown in figure 6, foam plastic insulation can be used on all six sides of residential and commercial building envelopes to perform a vast array of functions. It passively reduces heating and cooling loads, protects the building structure from the elements, provides occupant comfort, and can even provide extended occupant protection in power outages. When used as continuous insulation, it optimizes the thermal and moisture performance of building assemblies while also reducing the heating and cooling equipment sizes for further carbon reductions.

FIG. 6 Illustration of the many applications and functions of foam plastic insulated sheathing. Adapted from 2024 Applied Building Technology Group study.



Conclusions and Recommendations

Insulation is more essential than ever. It is not new and does not require great new investments before it is ready for prime time. All modern insulation materials, including foam plastics, have achieved low GWP. Manufacturers will likely continue to innovate to make their materials better and easier to use, but further advancements in lowering the GWP of insulation materials will likely come slower and with higher costs that may not be palatable to the market.

Insulation provides many benefits, but it is often overlooked or underutilized as a means to save energy, reduce total carbon emissions, and address affordable home and building ownership. The data presented in this paper support policies that promote the use of insulation to increase energy efficiency and minimize total carbon emissions. The following are areas that would benefit from additional data or policy improvements:

- More accurate and consistently applied carbon accounting for building materials is needed to benchmark and improve the embodied carbon of building materials globally.
- A greater number of building materials must begin to provide LCAs or EPDs to improve whole-building life cycle analysis and to better understand and prioritize embodied carbon improvements in the building sector.
- The insulation industry has made great strides in lowering the embodied carbon of insulation materials over the past several decades. Additional improvement in embodied carbon is likely possible but may come in smaller increments, may cost more, and may negatively affect other performance characteristics.
- Even when using NREL Cambium future clean grid scenarios, the payback period, or point at which the investment in embodied carbon becomes net positive carbon savings, is typically under 1 year for insulation, including foam plastics. These results indicate

that building envelope efficiency should be prioritized in carbon policy. Policies that focus solely on setting embodied carbon thresholds for insulation materials may actually harm overall building performance and cause missed opportunities to optimize the reduction of carbon in buildings.

- Due to the importance of insulation in saving energy and carbon and its role in providing resilience and many other functions, energy codes and related policy should be modified to properly value the long-term benefits of a well-insulated building envelope and prevent a misguided trade-off of prescriptive insulation requirements in exchange for more efficient heating, ventilation, and air conditioning (HVAC). Nor should insulation be allowed to be reduced by the increased use of renewable energy resources. HVAC efficiency and renewable energy are important as standalone technologies, but without a properly insulated envelope that saves vast amounts of energy and carbon, these measures will fall short of their full potential.

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