The high greenhouse gas price tag on residential building materials: True life cycle costs (and what can be done about them)

EFFICIENCY VERMONT R&D PROJECT: GREENHOUSE GAS REDUCTION

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Overview

Construction material choices can significantly affect the amount of embodied carbon—the full life cycle "cost" of carbon involved in building construction—as measured by the global warming potential (GWP) of the greenhouse gases (GHGs) associated with their manufacture and use.[1] How best to source and use the materials, and measure their effects, is still not well understood in the marketplace. Customers and contractors typically base their home insulation materials decisions on cost effectiveness, durability, regional availability of materials, and relevant building science, not on the materials' attendant GWP impacts.

This 2020 research and development project quantified GWP impacts of using low-GWP alternatives to common building materials and applied the results of the analysis to actual projects slated for construction. This study analyzed projects in residential new construction, and there is high relevance to existing homes and commercial construction.

Primary Aims of the Research

- Quantify GWP (in terms of CO_2e) for insulation materials, and identify and characterize high-priority substitutions for reference
- From an efficiency program point of view, determine the amount of an incentive, based on dollars / ton of CO_2e, necessary to motivate changes to current insulation practices on 3 to 5 residential new construction projects
- Obtain qualitative feedback from building professionals on the logistics / ease of material substitutions
- Explore non-GWP co-benefits, such as potential health impacts on installers and residents

This study also set an objective that extends beyond 2020: to determine whether builders who participated in the study (that is, those who received cost-offsetting funds for materials substitutions) have continued the lower-GWP substitutions in subsequent projects or reverted to pre-study practices.

Deliverables

- Reports on 3 to 5 Vermont homes built with lower GWP insulation materials compared to standard builder practice
- Summary of quantified CO_2e savings and incentive dollars per ton of CO_2e necessary to motivate changes to current insulation practice, for each home
- Internal tools and training for efficiency program staff
- External tools and training for contractors, installers, and homeowners

The deliverables set the stage to inform 2021 energy efficiency program design.

[1] GWP is the measure of GHG in carbon dioxide equivalence (CO_2e).

Quantifying GHG impacts

Background
Reducing GHG impacts of building construction tends to rest on discussions about materials. One such discussion has offered a carbon metric, but notes that there is "no broadly accepted mechanism for measuring building carbon emissions."[2]

To fill this gap, Efficiency Vermont has compiled common questions about what information is currently available that can be applied to a deeper analysis of real-world factors for an "accepted mechanism for measuring" embodied carbon:

- For new or existing buildings, what metrics can be used for embodied energy or carbon content of building materials?
- Is a whole-building lifecycle assessment needed?
- For a project whose builder/architect/homeowner wants to achieve maximum reductions for GWP, but without having to track it closely, what is the best way to estimate or specify a goal?

Life Cycle Assessments
Life Cycle Assessments (LCAs) contain characterizations of lifetime stages and associated impacts (Figure 1). In such an LCA, data for insulation materials are most consistently available for the product stage (modules A1-A3). This stage is also called *cradle to gate*—referring to the product cycle from extraction of materials from the earth to the point at which the completed product is ready to leave the factory. Other terms used in LCAs are *cradle to site* (modules A1-A5) and *cradle to grave* (modules A1-C4).

Module	A1-A3			A4-A5		B1-B7							C1-C4				D
Life cycle stages	Product stage			Construction process stage		Use stage							End-of-life stage				Benefits and loads beyond the system boundary stage
Processes	Raw material supply	Transport	Manufacturing	Transport	Construction-installation proces	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse, recovery, and recycling potential
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 1. Life cycle stages as defined in the European standard EN 15978[3]

[2] Edelson, Jim, 2019. *Efficiency and Carbon Reduction Goals Converge at the Built Environment*. Portland, OR: New Buildings Institute, https://newbuildings.org/efficiency-and-carbon-reduction-goals-converge-at-the-built-environment/.
[3] Trafik- og Byggestyrelsen (Danish Transport and Construction Agency), 2016. *Introduction to LCA of Buildings*. Copenhagen. https://www.trafikstyrelsen.dk/en/-/media/TBST-EN/Byggeri/Introduction-to-LCA-of-Buildings.pdf.

Environmental Product Declarations
Environmental Product Declarations (EPDs) detail LCA and other information relevant to a product's GWP, ozone depletion potential, water use, and other environmental impact categories. EPDs are valid for 5 years. They quantify environmental impact information in a way that allows comparisons among products.

ISO 21930 is the North American standard for building construction-related EPDs and EN 15804 is the standard for Europe. Both generally adhere to ISO 14025, which establishes the "rules" (procedures, format) for developing an EPD.[4] In reality, EPDs are relatively new and can vary widely in presentation and content. This can make true product comparisons challenging.

Product Classes Investigated
Residential new construction was the primary market for deciding what product classes to investigate. This study considered products common in the projects' building assemblies:

- Sub-slab
- Foundation / frost wall, interior
- Foundation / frost wall, exterior
- Above grade wall, cavity
- Above grade wall, continuous
- Joists
- Flat attic
- Sloped ceiling, cavity
- Sloped ceiling, continuous

The study then investigated the resulting insulation classes common to the above assemblies:

- Cellular glass, aggregate
- Cellulose, blown / loosefill and densepack
- Expanded polystyrene (EPS); Types I, II, IX, and VIII
- Fiberglass; batt, blown/loosefill, blown/spray, and board
- HempCrete, block
- Mineral wool; batt, blown, and board
- Phenolic foam, board
- Polyisocyanurate, board
- Spray polyurethane foam (SPF); 2K-LP, closed cell, open cell, roofing; hydrofluorocarbon (HFC), hydrofluoroolefin (HFO), water-blown
- Straw, panel
- Wood fiber, batt and board
- Extruded polystyrene (XPS); 15, 25, 40, 60, and 100 psi

Compiling the Database
Efficiency Vermont compiled a database of EPDs to assess GHG impacts, as a starting point to create a carbon calculator tool. Although the Embodied Carbon in Construction Calculator (EC3) is already on the market as an open-source tool, this study found that it lacked a convenient method for comparing all of the materials

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[4] *Environmental Product Declarations: Standards & Process*, provides a concise summary. Archecology, 2017, http://www.archecology.com/2017/04/03/environmental-product-declarations-standards-process/.

investigated here in equivalent terms.[5] Endeavour Centre has a similar database / tool to Efficiency Vermont's, but it is not available to the public.

For each insulation class, this research study analyzed its EPDs. Where possible, we sought three or more EPDs for a product class (for example, XPS foam board), and averaged them. However, there seemed to be a growing tendency (vs. pre-2020 investigative work) for industries to use a generic EPD, with averaged data across manufacturers and factories; that is, manufacturers did not singly invest in their own EPDs.

Priority was given to non-expired EPDs for products manufactured in North America and accepted European manufacture wherever no North American products existed, and the source of product was exclusively European. Two databases were the primary sources of the EPDs: EC3 and Sustainable Minds.[6] The Norwegian EPD Foundation[7] was a source for certain European EPDs.

To build and analyze this project's EPD database, the study team had to eliminate duplicate entries within source databases and examine EPDs that collectively covered more than one type of product. For example, the EC3 database had 187 EPDs for board insulation products, of which 130 were identical (the list contained each permutation of product name, manufacturing plant, and thickness; each permutation pointed to the same EPD). In some cases, an EPD covered several product types within a material class, with multiplication factors to be applied for each variant.

Analysis
The study team analyzed 79 EPDs. It excluded some from the summary because they were expired or pertinent for overseas markets; however, the study team compared those against current or North American EPDs. Also excluded were data from a small number of EPDs because they contained outlier data (on the order of one magnitude).

A lack of data consistency complicated the analysis and comparison of functional units. Because the majority used 1 m^2 of material at RSI-1 (the thickness of material required to reach RSI-1,[8] which translates to R-5.678 in imperial units) in this work, all outputs were standardized to 1 m^2 of RSI-1. Also, not all EPDs contained application data, which the study team looked up separately.

[5] Requires registration. See Building Transparency, n.d. "Embodied Carbon in Construction Calculator." https://www.buildingtransparency.org/en/
[6] Sustainable Minds Transparency Catalog. https://www.transparencycatalog.com/
[7] The foundation hosts a search function and offers supportive information about drafting EPDs at https://www.epd-norge.no/?lang=en_GB (the English language version of the site is not yet fully developed).
[8] *RSI* refers to thermal resistance in metric units, measured in m^2•K/W. R-value in the United States typically appears in the (unlabeled) units ft^2•°F•h/BTU.

For insulation materials, LCA data are most consistently available for Modules A1-A3 (**Figure 1**).

Module A4 is theoretically useful because it can differentiate locally sourced materials (and thus lower transportation impact), versus those shipped from afar. However, A4 was not taken into account here because (a) it is usually not included in LCAs, and (b) determining factory-to-site impacts would require knowing exactly from which factory a given material is sourced. To obtain that information would have required more time than was available to the project, and at least in part would have been dependent on successful supply chain tracing. Further, calculating factory-to-construction site data would have had to occur individually.

Modules B1-B7 (Use stage) are not, for most cases, valuable for differentiating materials. For example, the operational energy use (B6) of R-20 would be the same in Material X as for Material Y unless one material suffers performance degradation over time.

Beyond Modules A1-A3, the study team chose two other modules:

- **A5 (construction and installation process).** This module is important to consider for materials manufactured on site, such as spray polyurethane foam, to allow fair comparison for products manufactured in a factory setting (where the impacts of their refrigerants would be accounted for in Module A3 (manufacturing).
- **B1 (use).** This module considers materials that off-gas refrigerants over time. Refrigerants encapsulated in foam products can have significant GHG impacts.

The study team credited stored carbon content in terms of CO_2e, based on the mass of elemental carbon in the product. In some EPDs (for example, European wood fiber products), this was integrated into the GWP by default. In others, it needed to be calculated.

Efficiency Vermont summarized GWP (100 year value) and EPD-reported R-value per inch for certain materials (Table 1). The term *GWP** refers to the impact with A5, B1, and carbon storage. **Table 3,** in the **Appendix**, shows the complete GWP data, with all materials analyzed, including notes. This table also informed another 2020 Efficiency Vermont R&D project, *Embodied Carbon in Residential Retrofits.*

Table 1. Summary of global warming potential and R-values for frequently used construction materials

Material	**Form or variant**	**R-/"**	**GWP average, kgCO2e *[A1+A2+A3]* per 1m² RSI-1**	**GWP* average, kgCO2e *[w/A5+B1]* per 1m² RSI-1**	**GWP* includes**
Cellular glass	Aggregate	1.49	3.93	3.93	A5
Cellulose	Blown/loosefill, 1.29 pcf	3.38	0.49	-0.83	A5, carbon
Cellulose	Densepack, 3.55 pcf	3.56	1.27	-2.16	A5, carbon
Expanded polystyrene (EPS)	Board, unfaced Type IX-25psi, graph.	4.70	3.47	3.49	A5
Fiberglass	Batt, unfaced, recycled content	3.64	0.67	0.68	A5
Fiberglass	Blown/loosefill	2.68	1.29	1.30	A5
Fiberglass	Blown/spray	4.00	1.61	1.64	A5

Material	Form or variant	R-/"	GWP average, kgCO2e *[A1+A2+A3]* per 1m² RSI-1	GWP* average, kgCO2e *[w/A5+B1]* per 1m² RSI-1	GWP* includes
HempCrete	Block	2.14	-7.05	-5.67	A5, B1, carbon
Mineral wool	Batt, unfaced	4.24	3.11	3.25	A5 (1 EPD)
Mineral wool	Board, unfaced, "heavy" density	4.00	4.06	4.06	A5, B1
Phenolic foam	Board, glass tissue faced	7.21	1.54	1.54	Not given
Polyisocyanurate	Board, foil faced	6.53	2.32	2.32	Not given
Spray polyurethane foam	Spray, closed cell HFC	6.60	3.31	14.86	A5, B1
Spray polyurethane foam	Spray, closed cell HFO	6.60	3.47	4.00	A5, B1
Spray polyurethane foam	Spray, open cell	4.05	1.42	1.59	A5, B1
Straw	Panel	2.92	-10.95	-10.88	A5, B1, carbon
Wood fiber	Board, unfaced	3.47	-7.13	-7.13	Carbon
Extruded polystyrene (XPS)	Board, 25psi	5.00	20.17	46.51	A5, B1

Carbon-containing insulation materials (for example, cellulose and wood fiber) have the lowest GWP, in some cases *negative* values (indicating a net-positive impact). Generally, products without blowing agents or that use water or pentane[9] as a blowing agent come next. Materials with the highest GWP are those with HFC blowing agents.

Excel tool

To operationalize this work, the study team used data that informed Table 1 to create a building impacts calculator in Excel. The inputs were building assembly, installed / added R-value, total area (with framing), framing factor (zero for continuous insulation), baseline material, and comparison material. Cost was an optional impact factor.

The calculator used average GWP (A1-A3 and A5, B1, and carbon) for a given material to calculate GWP savings in absolute and percentage reduction terms. The team equated savings to miles driven by an average passenger vehicle, to provide a user with a frame of reference. Other frames of reference were number of 18-pound propane cylinders used up, pounds of coal burned, tons of waste recycled instead of landfilled, and tree seedlings grown for ten years.[10] **Figure 2** provides a sample calculation.

[9] Pentane is a relatively low-GWP hydrocarbon.
[10] Based on the EPA greenhouse gas equivalencies calculator, available at https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

User Inputs [Ensure that each entry is correct -- or left blank if not needed]										GHG impacts [Do not modify calculations]				
Building assembly [leave unused ones blank]	Insulation - *Base* [status quo material] [use drop-down]	Installed (added) R-value	Cost [optional]	Insulation - *Alternative* [for comparison] [use drop-down]	Installed (added) R-value2	Cost/ Added [optional]	Total area incl. framing [sq ft]	Framing factor [Cont = 0.00] [2x 16oc = 0.23] [2x 24oc = 0.20]	Include in summary?	GWP - *Base* [kg CO2e]	GWP - *Alternative* [kg CO2e]	Apples to Apples?	Incr. cost	GWP savings [kg CO2e]
Foundation_Slab	XPS - Board, 25psi	15	$1,722	EPS - Board, unfaced, Type IX - 25psi, graphite	15	$1,376	1120	0.00	Yes	12781	958	Yes	($346)	11823
Foundation_Slab	XPS - Board, 25psi	15	$1,722	Cellular glass - Aggregate	15	$990	1120	0.00	No	12781	1080	Yes	($732)	11701
Foundation_Ext_Wall	XPS - Board, 25psi	15	$1,083	EPS - Board, unfaced, Type IX - 25psi, graphite	15	$865	704	0.00	Yes	8034	602	Yes	($218)	7431
AGW_Continuous	XPS - Board, 25psi	15	$1,673	Polyiso - Board, foil faced	16	$2,406	1088	0.00	Yes	12416	661	No	$733	11755
Totals	Baseline			Alternative					Totals [kg CO2e]	33230	2221	No	$169	31009
									% reduction					93%
									m.t. CO2e					31.0
									Equivalance to:					
									Miles driven by average passenger vehicle					76,934
									Propane cylinders (18#) burned					1,268
									Pounds of coal burned					34,172
									Tons of waste recycled instead of landfilled					11
									Tree seedlings grown for 10 years					512

Figure 2. GWP building calculator snapshot.

This tool is currently available only to Efficiency Vermont staff. It informed a one-page summary for staff and customers (see Appendix), and was the basis for incentive offers to selected residential construction projects in 2020.

Case studies

High priority substitutions

Traditional insulation materials containing HFC blowing agents are by far the highest priority for substituting low-GWP / lower embodied carbon materials. For example, and as Table 1 shows, the GWP* of closed-cell spray polyurethane foam (with HFC blowing agent) per 1 m^2 of RSI-1 insulation is 14.86 kg CO_2e. For extruded polystyrene (all available product in United States as of the time of this research uses HFC blowing agents), it's 46.51 kg CO_2e. In contrast to these two high-GWP materials, closed-cell spray polyurethane foam using HFO blowing agent has a value of 4.00 kg CO_2e. For a mineral wool batt, it's 3.25 kg CO_2e. That value is partially driven by the energy-intensive process of melting glass, stone, or slag in manufacture. GWP is still lower for some products that use pentane (a relatively low-GWP hydrocarbon) as blowing agent: polyisocyanurate is 2.32 kg CO_2e and phenolic foam is 1.54 CO_2e. Fiberglass materials fare well, with unfaced batts less than 1 kg CO_2e. And carbon-containing insulation materials such as cellulose and wood fiber can have GWP less than zero, because they receive credit for storing carbon in the product itself.

Criteria

The team targeted repeat builders, architects, and building professionals who enrolled their services in Efficiency Vermont's residential programs. Although there were opportunities for one-off projects, the study team opted to use the available budget to share information and inspire action among those who were more likely to continue using lower-GWP materials in future projects—and thus enable us to capture data on their willingness to specify those materials with and without program incentives.

Project 1: Single-family affordable home in Bennington County

Overview

This was a planned single-story, slab-on-grade home, approximately 1,200 square feet. The builder builds 1 to 3 homes per year. Standard construction details specify XPS under slab and for the frost wall. Above-grade walls are typically mineral wool batts and XPS continuous insulation outside the sheathing.

Incentive Offer

Efficiency Vermont offered $1,250 to the builder for the following substitutions / deviations from their plan:

- **Under slab:** R-15 minimum, XPS replaced with suitable density EPS or a cellular glass aggregate product
- **Frost-protected foundation**: R-15 minimum, XPS replaced with suitable density EPS
- **Above-grade wall**: continuous insulation, R-15 minimum, XPS replaced with phenolic foam board or fiberboard

These substitutions would save an estimated 30 metric tons of CO_2e at an "acquisition cost" of GHGs reduced, at $40 per ton.

Status

The onset of the COVID-19 pandemic indefinitely postponed this planned build. The net cost, however, of the builder's planned substitutions was very low. With the information shared with the builder, this project could eventually proceed in 2021—but because this study has ended, it would have to proceed without efficiency program incentives.

Project 2: Quadplex in Chittenden County

Overview

This project has a footprint of approximately 2,600 square feet for the four units. Like Project 1, the builder constructs several homes each year. Prior to discussing the project with Efficiency Vermont, they planned to use XPS on below-grade / under-slab and on the exterior foundation wall. This was standard practice for them.

Incentive Offer

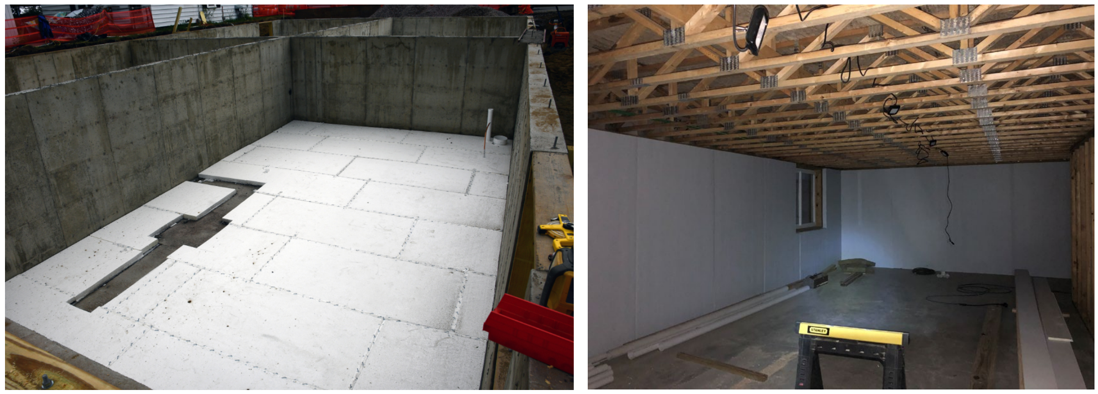
Efficiency Vermont offered $2,000 for the following substitutions / deviations from their plan:

- **Under slab**: R-15 minimum, XPS replaced with suitable density EPS or a cellular glass aggregate product
- **Foundation wall**: R-20 minimum, XPS replaced with suitable density EPS (exterior) or polyisocyanurate (interior)

These substitutions would save an estimated 52 metric tons of CO_2e at an acquisition cost of $38 per ton.

Status

The project is currently under construction and will complete by the end of 2020, with the substitutions listed above. The builder opted for EPS Type IX under the slab and interior-side polyisocyanurate for the foundation wall.



(a) (b)

Figure 3. (a) EPS sub-slab insulation, (b) polyisocyanurate interior foundation wall insulation.

Project 3: Single-family home in Chittenden County

Overview

This building is approximately 3,700 square feet and was under construction in August. An Efficiency Vermont energy consultant noticed the builder's plan for 4 inches of XPS on the exterior of its above-grade walls. The builder also planned XPS for all below-grade work. Efficiency Vermont offered incentives for substituting all XPS with lower-GWP materials, but the project's design team preferred to keep XPS below grade.

Incentive Offer

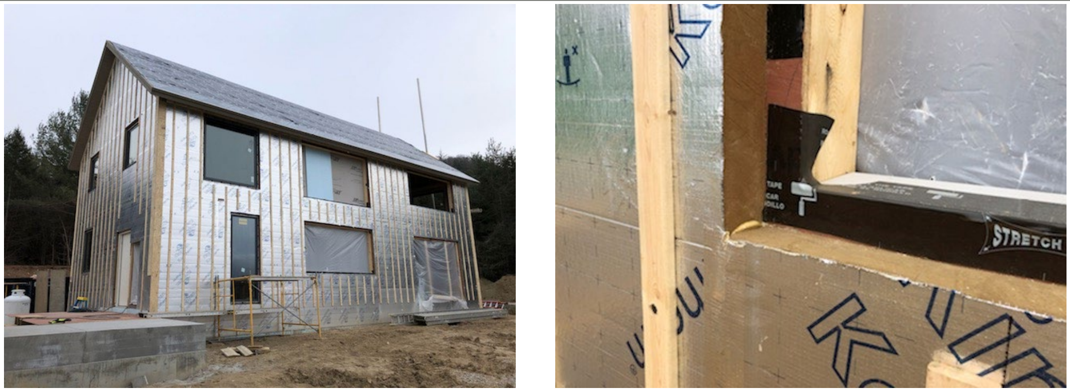
Efficiency Vermont offered $1,650 for the following substitution / deviation from their plan:

- **Above-grade wall**: continuous insulation, R-24 minimum, XPS replaced with phenolic foam board, fiberboard, or EPS

These substitutions would save an estimated 52 metric tons of CO_2e at an acquisition cost of $32 / ton.

Status

The builder-architect-homeowner team opted for phenolic foam board for the above-grade wall, exterior side. The project will complete by the end of 2020.



(a) (b)

Figure 4. (a) exterior insulation with strapping, (b) phenolic foam detail at window opening.

Co-benefits from substituting materials

GWP is not the only consideration for choosing insulation material. *The BuildingGreen Guide to Insulation* (3rd edition), summarizes insulation impacts by environmental attributes and health concerns, in addition to performance. The Guide lists hazardous components, chemical byproducts and residuals, fiber shedding, end-of-life issues, durability, and cost—all items that might not show up in an LCA.

Cellulose, for example, has high post-consumer-recycled content and regional manufacture that minimizes shipping costs. But it also frequently contains the flame retardant borate.[11] Loose fibers and dust can also be a respiratory irritant. For closed-cell spray polyurethane foam, details that don't stand out in an EPD relate to the material's proportion of recycled content, whether primary components are petroleum based, and whether the product is recyclable at the end of its lifetime. Further, methylene diphenyl diisocyanate, a toxic chemical, might be released during installation, making it vital that installers use proper protective equipment and unprotected people are evacuated for 24 to 72 hours after installation. Off-gassing of dangerous chemicals after installation is usually not a concern, but has been reported. **Table 2** groups common insulation materials according to GHG impact and contains notes on recycled content and toxic emissions. See also **Additional notes** at the conclusion of this report.

Table 2. Recycled content and toxic emissions potential of insulation materials

Material	GHG impact[a]	Recycled content[b]	Toxic emissions[c]	Notes[d]
Wood fiber	Lowest / best			
Cellulose	Lowest / best			
Fiberglass	Low			Avoid formaldehyde binders

[11] Another BuildingGreen publication notes that "Health concerns with borates have been thought to be low but are not well known; in 2011 the European Union added boric acid to the 'Candidate List' of potentially toxic chemicals in its REACH program, with concern about reproductive toxicity." Sawyer, Chris, 2017. "*Insulation Choices: What You Need to Know about Performance, Cost, Health and Environmental Considerations.* Brattleboro, Vermont: BuildingGreen: 39.

Material	GHG impact[a]	Recycled content[b]	Toxic emissions[c]	Notes[d]
Polyisocyanurate	Low			Chlorinated flame retardant (otherwise fairly inert) Toxic manufacturing process
EPS (expanded polystyrene)	Low			Brominated flame retardant
Open cell spray foam	Low			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
Phenolic foam	Low		See note	Phenol formaldehyde content, but low emissions
Mineral wool	Medium		See note	Choose low-emitting products
Closed-cell spray foam, HFO	Medium			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
Closed-cell spray foam, HFC	Highest / worst			Off-gassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
XPS (extruded polystyrene)	Highest / worst			Brominated flame retardant (otherwise fairly inert) Toxic manufacturing process

Sources: Efficiency Vermont analysis and *BuildingGreen Guide to Insulation*.

[a] Lowest: < 0 kgCO_2e including carbon content, per 1 m^2 RSI-1. Low: 0-5. Medium: 5-10. High > 10. Calculations are based on analysis within this report.

[b] From *BuildingGreen Guide*. Green indicates significant recycled content or renewable material. Red indicates little or no recycled content and fossil fuel-based materials in typical products.

[c] From *BuildingGreen*. Green indicates relatively low toxic emissions during use from typical products. Red indicates potential high toxic emissions from typical products or during manufacturing or application.

[d] From *BuildingGreen*, "Environmental Notes" in *Key Environmental and Performance Factors for Insulation Materials* table.

Discussion and future work

This R&D project succeeded in quantifying embodied carbon impacts of substituting common insulation materials. Efficiency Vermont was able to inform customer-facing energy consultants about the highest GWP products and alternatives worth investigating as replacements.

Other research on environmental and health concerns revealed that low-GWP insulation materials generally correlated with lower toxicity and higher recycled content.

An incentive of $30 to $40 per metric ton of averted CO_2e was a sufficient motivator for builders to participate in the small number of projects the study team worked with. For Project 3, it is unclear whether information sharing provided sufficient motivation for participation, or whether it was the financial incentive.

Several promising alternative insulation materials come at a high cost. Although there were cost savings associated with replacing XPS with EPS Type IX for below-grade applications, two examples of the inverse are:

- Several projects considered replacing above-grade wall exterior XPS with wood fiber boardstock, which has very low GWP. Unfortunately, all product options are currently imported from Europe and carry a significant price premium.
- Phenolic foam, another relatively low-GWP alternative to XPS for above-grade walls, has supply chain limitations that result in high costs. When

purchased by the truckload and compared on installed R-values, phenolic foam is cost competitive with XPS. But it is not stocked anywhere in Vermont and its price is significantly higher when ordered for a single project.

Another barrier to low-GWP substitutions is familiarity. One supplier stated that XPS is "tried and true" below grade. People trust it and know how to install it; it is considered a standard practice. Not surprising, many consider deviations from that practice to be a risk.

XPS and closed-cell spray foam using an HFC blowing agent were the two "worst" products from the GWP perspective. Legislation in Vermont will soon change this: On January 1, 2021, XPS (boardstock and billet) and two-component spray foam (high pressure and low pressure) will be prohibited from using certain HFCs and related blends.[12] If XPS and closed-cell spray foam products become widely available, using HFOs and / or natural refrigerants in place of HFCs, the GWP-based economics of substituting these products will become less advantageous. The downsides of such materials, noted in **Table 2**, are not expected to be improved by using a different blowing agent.

None of the three new-construction projects has yet been completed. When they do approach or reach completion, Efficiency Vermont hopes through interviews to:

- Obtain feedback on the logistics / ease of material substitutions, ideally getting some sharable quotes or anecdotes
- Gain perspective on their added or avoided costs from the substitution
- Learn whether they plan to repeat the substitutions in future projects (and monitor this over time)
- Share more information with installers and residents on the co-benefits of potential positive health impacts from these substituted materials

This R&D project has obtained sufficient information to warrant further research, using the data from this project as a solid foundation. To extend the value of the project, Efficiency Vermont intends to:

- Distribute the building calculator tool to more staff, encouraging its use on many new and existing residential and commercial building applications
- Deliver training for in-house energy consultants, account managers, and program staff
- Build out our web-based reference on GWP and construction material substitutions
- Investigate roadblocks to low-GWP substitutions, especially lack of awareness and supply chain / cost barriers

In addition, Efficiency Vermont plans in 2021 to:

[12] Ref. S.30 (Act 65), 2019, https://legislature.vermont.gov/bill/status/2020/S.30; and *Rules regarding phase-down of the use of Hydrofluorocarbons*, available at https://dec.vermont.gov/air-quality/laws/recent-regs.

- Design and deliver an Efficiency Excellence Network session on lower-GWP materials and applications for the Efficiency Vermont contractor network
- Present findings at the Better Buildings by Design conference in 2021
- Post a paper on this work, for the Efficiency Vermont website
- Pitch articles to venues such as GreenBuildingAdvisor.com, the *Journal of Light Construction*, and *Fine Homebuilding*

Appendix

Table 3
Summary of GWP and R-values, by insulation material

Figure 5
Carbon drawdown in your next construction project
One-page summary of GWP impacts, for Efficiency Vermont staff and external use, also available at https://www.efficiencyvermont.com/Media/Default/docs/printable-resources/GeneralInfoForHomes/EVT-Home-Insulation-GHG-OnePager.pdf

Table 3. Summary of GWP and R-values, by insulation material

Material	Form or variant	Blowing agent	R-/"	GWP range, kgCO2e *[A1+A2+A3]* (per 1m² RSI-1)	GWP average, kgCO2e *[A1+A2+A3]* (per 1m² RSI-1)	GWP* average, kgCO2e *[w/A5+B1]* (per 1m² RSI-1)	GWP* includes	Basis / notes
Cellular glass	Aggregate	NA	1.49	NA	3.93	3.93	A5	1 EPD
Cellulose	Blown/loosefill, 1.29 pcf	NA	3.38	NA	0.49	-0.83	A5, carbon	Used North American industry EPD; similar magnitude to 2 European EPDs
Cellulose	Densepack, 3.55 pcf	NA	3.56	NA	1.27	-2.16	A5, carbon	Used North American industry EPD; similar magnitude to 2 European EPDs, scaled to densepack application
Expanded polystyrene (EPS)	Board, unfaced, Type I - 10psi	Pentane	3.60	NA	2.63	2.63	A5, B1	Used North American industry EPD
Expanded polystyrene (EPS)	Board, unfaced, Type I - 10psi, graphite	Pentane	4.70	1.73-1.74	1.74	1.78	A5	Average of 2 North American products
Expanded polystyrene (EPS)	Board, unfaced, Type II - 15psi, graphite	Pentane	4.70	2.78-2.80	2.79	2.80	A5	Average of 2 North American products
Expanded polystyrene (EPS)	Board, unfaced, Type IX - 25psi, graphite	Pentane	4.70	3.46-3.49	3.47	3.49	A5	Average of 2 North American products
Expanded polystyrene (EPS)	Board, unfaced, Type VIII - 13psi, graphite	Pentane	4.70	2.21-2.24	2.22	2.23	A5	Average of 2 North American products
Fiberglass	Batt, unfaced, recycled content	NA	3.64	0.46-0.94	0.67	0.68	A5	Average of 3 North American products, with recycled content
Fiberglass	Blown/loosefill	NA	2.68	NA	1.29	1.30	A5	1 EPD
Fiberglass	Blown/spray	NA	4.00	1.29-1.93	1.61	1.64	A5	Average of 2 North American products
Fiberglass	Board, unfaced	NA	4.23	5.56-9.12	7.34	7.37	A5	Average of 2 North American products
HempCrete	Block	NA	2.14	NA	-7.05	-5.67	A5, B1, carbon	1 EPD; embodied carbon incl. in A1-A3, accounts for carbonization of blocks, 240 days after production
Mineral wool	Batt, unfaced	NA	4.24	1.44-4.77	3.11	3.25	A5 (1 EPD)	2 EPDs; Owens Corning has formaldehyde free variant but not included in summary
Mineral wool	Blown	NA	2.95	NA	5.16	5.18	A5	1 EPD
Mineral wool	Board, unfaced, Thermafiber "medium" density	NA	4.30	NA	9.71	9.71	A5	1 EPD
Mineral wool	Board, unfaced, Rockwool "heavy" density	NA	4.00	NA	4.06	4.06	A5, B1	1 EPD
Mineral wool	Board, unfaced, Rockwool "heaviest" density	NA	4.00	NA	5.63	5.63	A5, B1	1 EPD
Phenolic foam	Board, glass tissue faced	Pentane	7.21	NA	1.54	1.54	Not given	1 EPD (only commercially available), based on K5 version of product
Polyisocyanurate	Board, foil faced	Pentane	6.53	NA	2.32	2.32	Not given	Used North American industry EPD
Polyisocyanurate	Board, GRF facers (roof appl)	Pentane	5.76	2.19-2.80	2.47	2.63	A5 (for 2 EPDs)	Average of North American industry EPD and 2 manufacturers
Spray polyurethane foam (SPF)	Spray, 2K-LP HFC	HFC	6.15	NA	3.21	25.46	A5, B1	Used North American industry EPD; B1 approx. 2x impact of A5
Spray polyurethane foam (SPF)	Spray, closed cell HFC	HFC	6.60	NA	3.31	14.86	A5, B1	Used North American industry EPD; B1 approx. 2x impact of A5
Spray polyurethane foam (SPF)	Spray, closed cell HFO	HFO	6.60	NA	3.47	4.00	A5, B1	Used North American industry EPD; no B1 impacts
Spray polyurethane foam (SPF)	Spray, open cell	Water	4.05	NA	1.42	1.59	A5, B1	Used North American industry EPD; no B1 impacts
Spray polyurethane foam (SPF)	Spray, roofing HFC	HFC	6.50	NA	3.83	19.33	A5, B1	Used North American industry EPD; B1 approx. 2x impact of A5
Spray polyurethane foam (SPF)	Spray, roofing HFO	HFO	6.50	NA	4.05	4.74	A5, B1	Used North American industry EPD; no B1 impacts
Straw	Panel	NA	2.92	NA	-10.95	-10.88	A5, B1, carbon	1 EPD; embodied carbon incl. in A1-A3
Wood fiber	Batt, unfaced	NA	3.76	-2.11- -1.82	-1.96	-1.96	Carbon	Average of 2 EU products; EPDs include embodied carbon / not broken out separately
Wood fiber	Board, unfaced	NA	3.47	-8.57- -5.69	-7.13	-7.13	Carbon	Average of 2 EU products; EPDs include embodied carbon / not broken out separately
Extruded polystyrene (XPS)	Board, 15psi	HFC	4.99	NA	16.93	39.04	A5, B1	1 EPD; A5 impact negligible, B1 impact enormous
Extruded polystyrene (XPS)	Board, 25psi	HFC	5.00	NA	20.17	46.51	A5, B1	1 EPD; A5 impact negligible, B1 impact enormous
Extruded polystyrene (XPS)	Board, 40psi	HFC	5.00	NA	23.43	54.04	A5, B1	1 EPD; A5 impact negligible, B1 impact enormous
Extruded polystyrene (XPS)	Board, 60psi	HFC	5.00	NA	28.65	66.06	A5, B1	1 EPD; A5 impact negligible, B1 impact enormous
Extruded polystyrene (XPS)	Board, 100psi	HFC	5.00	NA	39.05	90.05	A5, B1	1 EPD; A5 impact negligible, B1 impact enormous

Carbon drawdown in your next construction project

Choosing insulation materials with the lowest greenhouse gas impact

Embodied carbon refers to the greenhouse gas (GHG) emissions that went into the production of materials. A summary of common insulation materials appears in the table below. Materials that contain carbon and/or require less energy to produce have the lowest (best) GHG impact. At the other end, materials with high-GHG refrigerants tend to have the worst carbon footprint.[1]

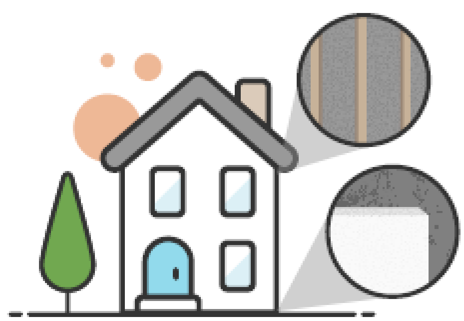
Material	Example manufacturers / products	GHG Impact[2]	Notes
Wood fiber	Steico, Gutex	Lowest / Best	Boardstock, batts
Cellulose	Cleanfiber, GreenFiber	Lowest / Best	Densepack, loosefill
Fiberglass	CertainTeed Sustainable, Knauf EcoBatt	Low	Batts, boardstock, loosefill/densepack
Polyisocyanurate	DuPont Thermax	Low	Boardstock; Blowing agent: pentane
EPS (expanded polystyrene)	Atlas, BASF Neopor	Low	Boardstock; Blowing agent: pentane
Open cell spray foam	Demilec APX, Lapolla Foam-Lok 450	Low	Site-blown; Blowing agent: water
Phenolic foam	Kingspan Kooltherm	Low	Boardstock; Blowing agent: pentane
Mineral wool	Rockwool, Owens Corning	Medium	Batts, boardstock
Closed cell spray foam, HFO	Demilec Heatlok HFO Pro, Lapolla ProSeal HFO	Medium	Site-blown; Blowing agent: HFOs
Closed cell spray foam, HFC	Demilec Heatlok XT, Dow Froth-Pak	Highest / Worst	Site-blown; Blowing agent: HFCs
XPS (extruded polystyrene)	Dow Styrofoam (blueboard), Owens Corning (pinkboard)	Highest / Worst	Boardstock; Blowing agent: HFCs

Partners have shared that many material substitutions are not only easy to implement, they can actually save money. Furthermore, many lower-GHG materials are less toxic to workers and/or building occupants.[3]

Example: A 2-story, 2000 square foot home making insulation substitutions detailed below avoids approx. 55,000 kg CO_2e, roughly equal to *not* driving 136,000 miles or *not* burning 60,000 pounds of coal. Provided the installed R-value is the same and proper air sealing is done, there is no significant difference between the two homes' operational energy.

GHG Impact: High

- XPS for sub-slab and foundation
- HFC-based spray foams in walls and cathedral ceiling



GHG Impact: Low

- EPS Type IX for sub-slab and polyisocyanurate (interior) foundation
- Densepack cellulose in walls and cathedral ceiling

[1] Our analysis is based on Cradle to Gate: extraction of resources from the earth until the point that a product leaves the factory. This corresponds to Life Cycle Assessment product stages A1, A2, and A3. We also include A5 for materials manufactured on-site (such as spray polyurethane foam that emits refrigerant at installation) and B1 (which is important to consider for insulations which off-gas refrigerants over time).
[2] Lowest: < 0 $kgCO_2e$ including carbon content, per 1 m_2 RSI-1. Low: 0-5. Medium: 5-10. High > 10.
[3] A useful summary of cost, health, and environmental considerations of insulation materials is available at: https://www.buildinggreen.com/sites/default/files/BG_Insulation_Recommendations.pdf

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Figure 5. One-page summary of GWP impacts, for staff and external use.