The Climate Impact of Retrofits: Embodied and Operational Emissions in Weatherization

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ABSTRACT

As buildings become part of the climate change solution, more building professionals and their customers want to know how to reduce carbon emissions in home retrofits. Meanwhile, community leaders seek strategies for increased equity for the most vulnerable of their communities.

This study assesses the carbon impact of insulation and air sealing upgrades when accounting for both embodied carbon emissions of materials and operational carbon reductions resulting from weatherization upgrades. A comparison is made between the most common insulation practice (closed cell spray foam) and readily available and cost competitive "Carbon Smart" insulation practices (dense pack cellulose and polyisocyanurate) to evaluate overall carbon impact. The research team calculated the time period required to equalize the upfront embodied carbon emissions for specific installed weatherization practices in basements, walls, and ceilings with the estimated operational carbon emissions avoided.

The team found that when using closed cell spray foam the operational carbon savings overtake embodied carbon emissions in two years. Carbon Smart practices result in net carbon savings within the first year due to the use of low embodied carbon and carbon-storing materials. The use of spray foam at all applications realizes total emissions over ten years that are 15% higher than the use of "Carbon Smart- Equivalent R-Value" approaches for all applications. However, given the high rate of operational emissions for a typical cold-climate home, conducting weatherization work regardless of the material used is beneficial to the home's total carbon emissions within a short timeframe while also reducing energy costs.

Introduction

Nearly everyone addressing climate change now recognizes that decarbonizing buildings is an essential solution for reducing greenhouse gas emissions. As the number of home weatherization projects begins to increase, homeowners and building professionals can apply lessons learned from studies of greenhouse gas retrofits. A Vermont architect, a local construction contractor, and the statewide energy efficiency utility (Efficiency Vermont) conducted a greenhouse gas retrofit study in 2020 investigating the embodied carbon impact of insulation materials commonly used in weatherization (Nedzinski et al. 2020). One year later, the authors have now assessed the carbon impact of weatherization material choices, and accounted for reduced operational carbon emissions from weatherization upgrades.

Data for the current study come primarily from Efficiency Vermont's Home Performance with ENERGY STAR® (HPwES) program and the Vermont Department of Public Service's

"Vermont Single-Family Existing Homes Overall Report" (NMR 2019). These data detail effects of the most common insulation practices, providing the basis for the team's comparison to a home using low-carbon insulation practices. The purpose of the current study is to compare how the carbon emissions for specific applications can inform material choices at the outset of a project and optimize carbon emissions over time.

Methods

The current study modeled four scenarios, ranging from a baseline scenario to Common Practice, Carbon Smart, and a Carbon Smart (Equivalent-R) scenarios.

The research team created an OpenStudio (OS) energy model in the OS Parametric Analysis Tool (PAT), entering building characteristics such as total conditioned square feet, assembly R-values, and mechanical system efficiencies. The PAT generates a Home Performance XML building description file that is converted to an OS model. The team then performed an EnergyPlus hourly simulation on the OS energy model, running simulations for each component and variable efficiency value for each application and scenario.

The results thus are expressed in gallons of fuel oil reduced by weatherization upgrades. The team excluded the impact of kilowatt-hour (kWh) use for non-heating energy, because there was no change in fenestration, mechanical equipment, building configuration, lighting, or assumed plug loads. The team also calculated the amount of reduced carbon dioxide-equivalent gases (CO_2e) for each measure or measure combination, compared to baseline. Using the U.S. Environmental Protection Agency's calculation methods (EPA 2020), the team also converted gallons of oil to kilograms of CO_2e, with the formula:

The average carbon dioxide coefficient of distillate fuel oil is 430.80 kg CO_2 *per 42-gallon barrel.*

Material Types and Quantities

The team calculated the quantity of material / type of insulation used in each project application from the number of inches of material for each type of insulation installed and based on information derived from the two aforementioned datasets.

All measures assumed hydrofluoroolefin (HFO)-type closed-cell spray polyurethane foam (SPF) for Common Practice scenarios, and dense pack cellulose for Carbon Smart materials scenarios.[1] The exception was foundation walls, which assumed foil-faced polyisocyanurate for the Carbon Smart scenarios. The team included foil-faced polyisocyanurate board insulation in the Carbon Smart foundation wall scenario because it is commonly available and moisture and installation considerations are similar to that of the "Common Practice" scenario. Although alternative strategies exist for insulating foundation walls with less carbon-intensive materials (for example, wood fiberboard and cellulose), those strategies required additional moisture and installation considerations and risk, and therefore are less common.

The team used the global warming potential (GWP) value of HFO-type closed-cell SPF insulation to reflect the growing use of this material (Nedzinski et al. 2020), and because of

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[1] Carbon-smart materials are those that have lower carbon emissions or are carbon sequestering.

statewide legislation, and the expected near-term phaseout of the more carbon-intensive HFC-based products (Vermont General Assembly 2019).

Carbon Emissions and Storage

The team calculated embodied carbon emission values, by project application, using a VEIC 2020 Environmental Product Declaration (EPD) calculator (Just 2020).

Carbon storage values were included only for cellulose insulation, as the only material featuring a significant percentage of biogenic material (Just 2020). The authors hold confidence including this valuation of stored carbon due to the predominant source of cellulose insulation being recycled paper and cardboard diverted from the waste stream.

Included Life Cycle Assessment (LCA) Stages

The study focused on "up front" embodied carbon emissions beginning with material extraction through installation. Specifically, Product Stage (A1-A3), *cradle-to-gate* portion of the life cycle assessment (LCA) to determine embodied carbon in insulation material production. Installation process (A5) and use (B1) were included where applicable to account for carbon emissions associated with those phases (e.g. emissions associated with spray foam blowing agents [A5] and additional post-install emissions release from foam products [B1]).

Other emissions during phases A5 and B1, such as worker and material transportation to site, were not included in this study. Ten years was assumed as the time boundary of this study.[2]

Research Tasks

To determine carbon impact, the team created three essential research tasks:

Research task 1. Compare first-year operational energy emissions (modeled) for each scenario compared to Baseline. Compare first-year operational energy emissions (modeled) savings, relative to the baseline, "do nothing" scenario, for each scenario and for each weatherization measure individually.

Research task 2. Compare first-year carbon impact, calculated as embodied carbon emissions + first-year operational carbon emissions (modeled), for each scenario compared to Baseline, and for each weatherization measure individually.

Research task 3. Compare carbon impact over time, calculated as embodied carbon emissions + first-year operational carbon emissions (modeled) + (annual modeled operational carbon

[2] B1 emissions for HFO SPF equates to only 0.2% of the A1-A3 emissions for this product, and accordingly are negligible in their impact.

emissions x number of years). This was calculated for each scenario compared to the Baseline scenario, and for each weatherization measure individually.

The Scenarios

“Baseline” and “Common Practice” scenarios. Data were derived from the Efficiency Vermont Home Performance with ENERGY STAR 2012–2016 data set from contractor inputs in the energy efficiency utility’s Home Energy Reporting Online (HERO) tool. The study team filtered the data[3] to identify only completed projects with installed measures. This data set was the primary source of data the team used for both the Baseline and the Common Practice weatherization scenarios. The HERO data were cross-referenced with the Vermont Department of Public Service’s “Vermont Single-Family Existing Homes Overall Report” (NMR 2019). Additionally, where HERO data were lacking or insufficient to establish Baseline and Common Practice data for inclusion in the OpenStudio model, the team used the “Vermont Single-Family Existing Homes Overall Report” as a data source (NMR 2019). Examples of building characteristic values obtained from the report are conditioned floor area, heating system type, and window assumptions.

“Carbon Smart” weatherization scenario. The Carbon Smart scenario focused on replacing higher embodied carbon materials with lower embodied carbon materials (e.g., replacing spray foam insulation with dense pack cellulose). The authors reviewed the Baseline and Common Practice data set for each application to determine a typical R-value. A typical framing cavity was derived from these data by dividing the total assembly R-value by the R-value per inch of the material used. The team then cross-referenced this information with the “Vermont Single-Family Existing Homes Overall Report,” which confirmed each assumption to be reasonable (NMR 2019). The calculated typical framing depth was then assumed as the available cavity to receive a lower-embodied carbon weatherization material. In several instances an equivalent R-value to match the Common Practice R-values could not be achieved due to limitations of the existing framing depths, or due to the need to include code-required ventilation space for relevant cellulose assemblies. The team assumed caulking was used at the dense pack cellulose applications to achieve the modeled air-sealing improvements.

“Carbon Smart (Equivalent-R)” weatherization scenario. In this scenario, the materials used at each application remained the same as those in the Carbon Smart scenario; however, the R-value was increased to match that of the Common Practice scenario. The additional embodied carbon impact associated with the increase of the weatherization materials used (cellulose, board insulation, air-sealing caulk, etc.) was included in the analysis, where applicable.

Modeling Assumptions

Embodied carbon impacts of materials. In each of the weatherization scenarios, the team included both the embodied carbon impact associated with the insulation and air-sealing in the

[3] The original dataset included 12,849 installed insulation measures. That data was sorted to include: below grade basement, band joist, above grade wall and closed cavity ceiling measures (7,958 measures in total).

analysis. See Table 1 for assumed R-values and embodied carbon emissions data specific to each material.

Table 1. Global warming potential (GWP) of insulation material and R-value summary (Just 2020)

Material	Form or variant	R-value/ inch	100 yr. GWP average kg CO2e [A1-A3 w / A5+B1] per m2 RSI-1	GWP components
Cellulose	Dense pack, 3.55 pcf	3.56	-2.16	A1-A3, A5, B1 carbon storage
Polyisocyanurate	Board, foil-faced	6.53	2.32	A1-A3; A5, B1 not given
Spray polyurethane foam (SPF)	Spray, closed-cell hydrofluorocarbons (HFC)4	6.60	14.86	A1-A3, A5, B1
Spray polyurethane foam (SPF)	Spray, closed-cell hydrofluoroolefins (HFO)	6.60	4.00	A1-A3, A5, B1
Air-sealing Caulking[5]	Siliconized Acrylic Sealant	N/A	1.7	A1-A3

The authors did not include the additional embodied carbon impacts for the removal and replacement of finishes, added strapping, or other means of providing access or increasing framing depths in any of the scenarios**.**

Air infiltration. The existing air infiltration rate was assumed as 12 ACH50 in the Baseline scenario. The team obtained this value by calculating the average pre-weatherization air leakage rate for homes in the 2,000–2,999 square foot size bin from the HERO data set. The data set was filtered to best represent the "typical" Vermont existing home size of 2,200 square feet used for

[4] Although HFC-type foam was not included in this analysis, it is included in Table 1 to illustrate the relative difference in global warming potential between HFO and HFC closed-cell spray foam.

[5] This material was not included in the study referenced by footnote 6 and was calculated from Top Gun Sealants EPD https://info.nsf.org/Certified/Sustain/ProdCert/EPD10137.pdf for 200XI Siliconized Acrylic Sealant White. Assumed values were: EPD Declared Unit: 1kg, EPD Yield: 31m/kg, EPD value (A1-A3): 1.7kg/CO2e/kg.

modeling. The team also obtained average air leakage reduction post-weatherization from the HERO data set which determined the 30% air-infiltration improvement, or 8.4 ACH50.

Based on HERO data, the team calculated the following air leakage reductions, per application, which were included in the energy model: Foundation, 0% air leakage reduction[6]; band joist, 17% air leakage reduction; above-grade walls, 8.3% air leakage reduction; closed cavity ceiling, 4.7% air leakage reduction.

Energy model verification. The authors referenced a 2020 study released by the State of Wisconsin evaluating energy consumption of projects in its weatherization program, to verify modeled energy usage against a data set of measured energy usage, since such a study was not available from a Vermont data set (Lick et al. 2020). Given a comparable heating climate, this study provides a point of reference for the accuracy of this study's modeled data.

In the Wisconsin study, collected metered heating fuel data were analyzed for approximately 4,000 single-family homes in 2019. The Vermont team shows a modeled energy reduction of 36%; accordingly, the Wisconsin study's measured average percentage of energy reduction of 17%. This is primarily due to a modeled baseline for the "typical Vermont home" that has higher energy consumption than the measured average baseline in the Wisconsin study, as well as a slightly lower modeled energy use for the improved "typical Vermont home" compared with the measured improved energy use in the Wisconsin study.

The authors believe these deviations fall within expected margins of error for average annual energy modeling of large data sets, and hold confidence in the validity of the energy model to reasonably represent actual energy usage in buildings within the study focus. The U.S. Department of Energy and National Renewable Energy Laboratory have reported that behavior can account for +/-14% of energy use (Glickman 2014) and that median absolute modeled to measured heating energy use varies from 24% to 37% for commonly used residential modeling tools (Roberts et al. 2012).

Additionally, the significant deviation in percentage of energy reduction points toward a possibility that the modeled results overestimate energy reduction; more likely, the authors expect that the insulation and air-sealing improvements modeled in this study based on Home Performance with ENERGY STAR projects exceed the levels conducted in the Wisconsin study, and that this accounts for the study's relatively greater energy reductions. Additionally, the Vermont model assumed 2x4 above grade walls and only sloped ceilings, generating a "typical" home model that is more representative of a higher energy-use baseline home. The Wisconsin study noted that the highest energy users in the study, those using over 1,400 therms per year, yielded the greatest savings in the 25–30% range which aligns with our modeled home results.

Results and Analysis

Research Task 1 – First Year Operational Carbon Emissions Impact

This task calculated the approximate operational carbon savings when a typical existing Vermont home was weatherized with the most commonly adopted HPwES practices. Figure 1

[6] This area is assumed to be below grade through solid poured concrete or mortared block walls, therefore assumed to have negligible air leakage.

shows the first year of operational carbon emissions for each of the modeled scenarios, including the Baseline scenario. In the Baseline "do nothing" scenario, no weatherization improvements were made.

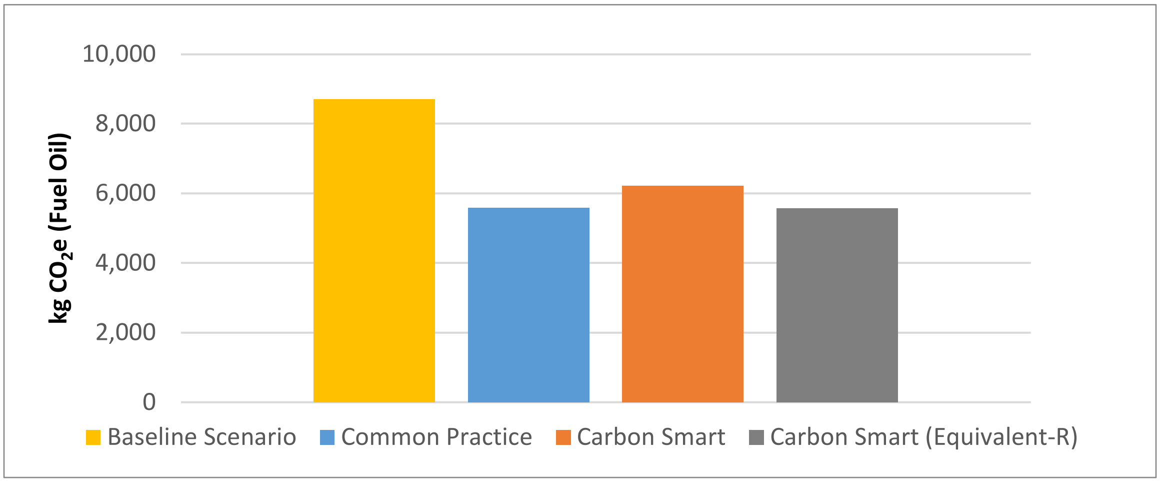

Figure 1. First-year operational kilograms of CO_2e emissions, for all measures.

Figure 2 shows the modeled results for the first year of operational emission savings of the three weatherization scenarios relative to a "typical Vermont home" with no weatherization as the baseline. The approximately 500 kg of CO_2e difference between the Common Practice and Carbon Smart weatherization scenarios illustrated here is equivalent to the emissions associated with driving an average car approximately 1,200 miles, or by consuming 56 gal of gasoline (EPA 2020). The operational emission savings of the Carbon Smart scenario are less than those of the Common Practice because the spray foam used in the Common Practice has a higher R-value per installed inch than the cellulose used in the Carbon Smart scenario, and therefore provides a greater R-value within a fixed cavity depth. Carbon Smart (Equivalent-R) removes this constraint.

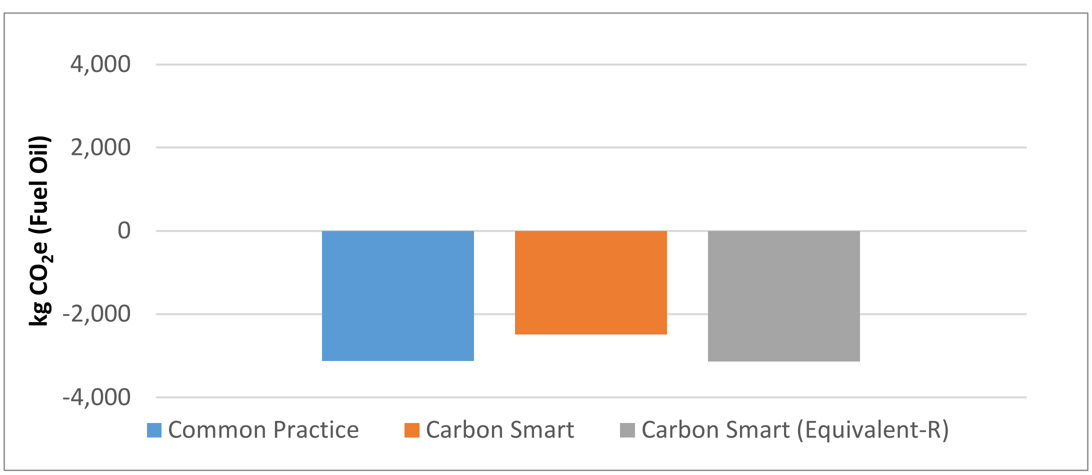

Figure 2. First-year operational CO2e savings, in kilograms, compared to the Baseline condition for all measures.

Figure 3 shows the modeled results for the first year of operational emissions savings of the three weatherization scenarios relative to the "typical Vermont home" baseline scenario by individual measure. As illustrated here, the existing wall and ceiling framing cavities prevented the Carbon Smart scenario from achieving an equivalent R-value to the Common Practice scenario.

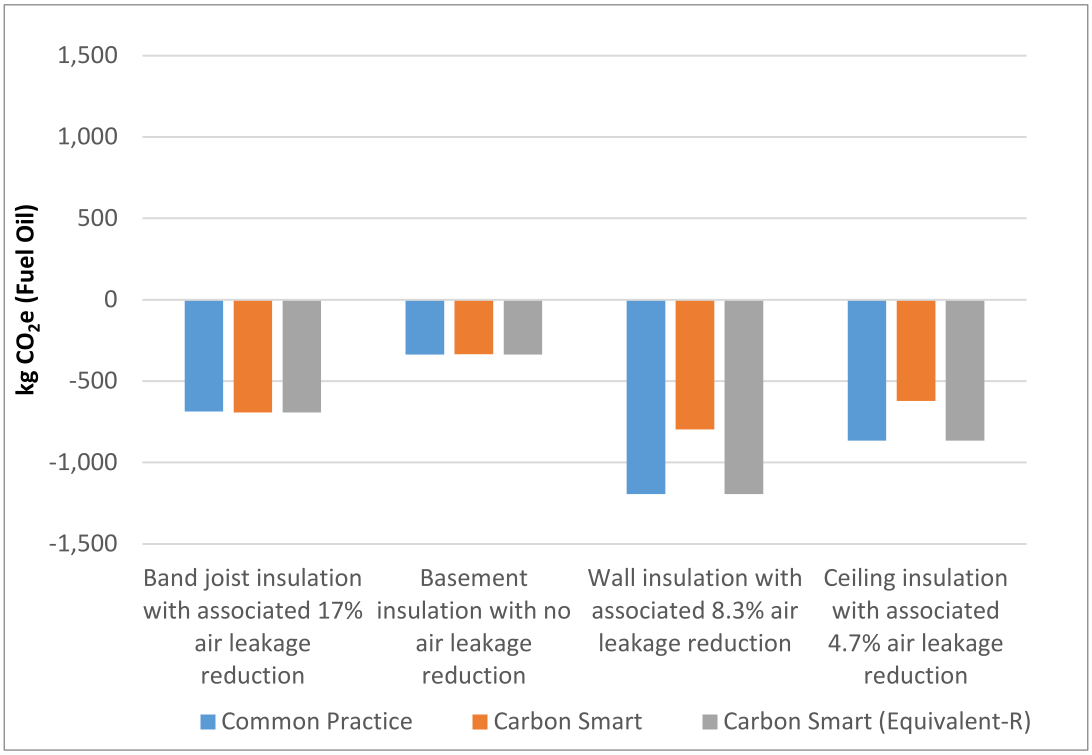

Figure 3. First-year operational savings of CO2e, in kilograms, by measure, compared to the Baseline.

Research Task 2 – First Year Embodied and Operational Carbon Impact after Weatherization

This task calculated the carbon impact (operational and embodied carbon) for the first year following the weatherization of a typical Vermont home, using the most commonly adopted HPwES practices and using low-carbon materials and approaches.

Figure 4 illustrates the first year of modeled operational carbon emissions combined with the embodied carbon emissions of the insulation materials employed at all applications for the various weatherization scenarios.

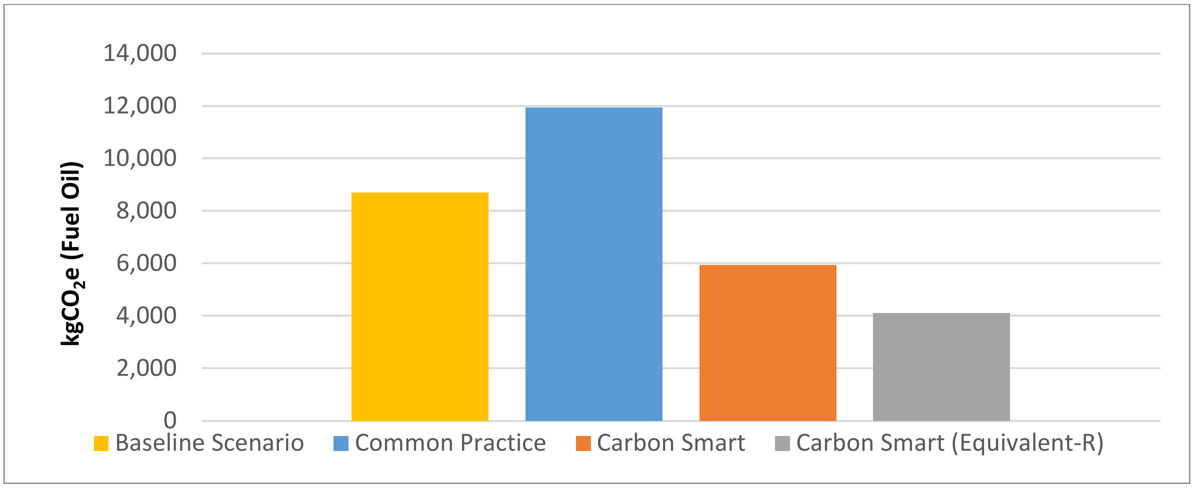

Figure 4. First-year operational and embodied CO_2e emissions, in kilograms, for a weatherized house, all measures.

In the first year, the Common Practice scenario represents approximately a 50% increase in carbon emissions over the Baseline, “do-nothing,” scenario, and approximately twice the emissions of the Carbon Smart scenario. The Carbon Smart and Carbon Smart (Equivalent-R) scenarios represent approximately a 25% and greater than 50% emissions reduction below Baseline, respectively, for the first year (Figure 4).

Figure 5 breaks down the results shown in Figure 4 to illustrate the carbon emissions (embodied and operational) by measure for each of the various weatherization scenarios.

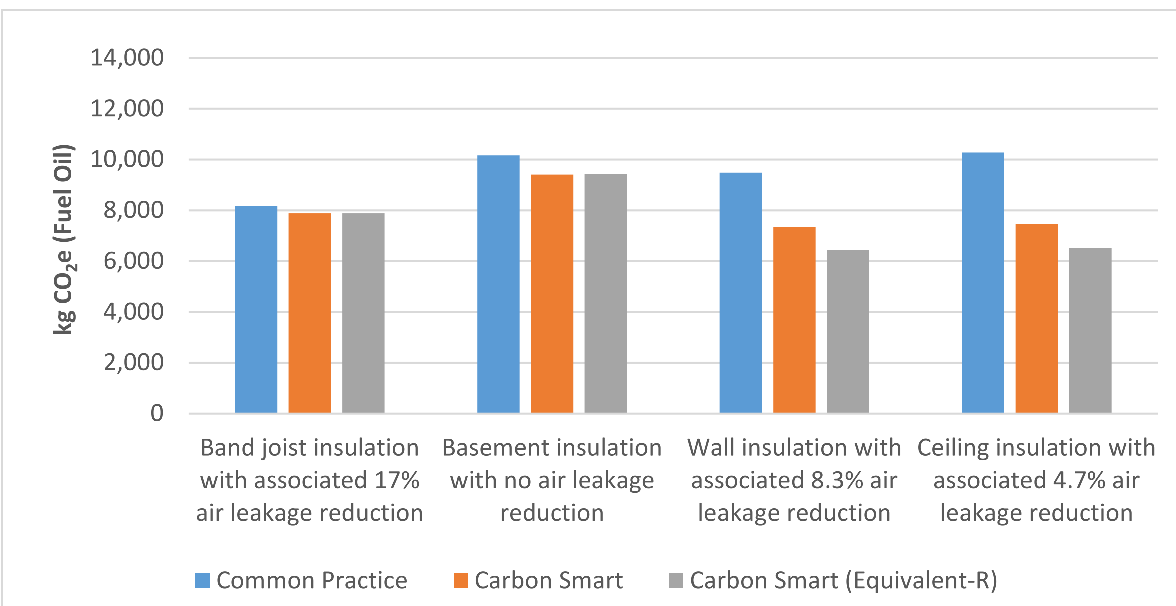

Figure 5. First-year operational and embodied CO_2e emissions, in kilograms, by measure.

Research Task 3 – Determining the Time for Equalizing Operational and Embodied Emissions

This task calculated the time period required to equalize the up-front embodied carbon emissions for specific installed weatherization practices, with the estimated operational carbon emissions avoided. It assumed the most commonly adopted HPwES practices and the use of low-carbon materials and strategies.

Figure 6 illustrates the embodied carbon emissions of the weatherization materials employed at all applications and their associated operational carbon emissions over time.

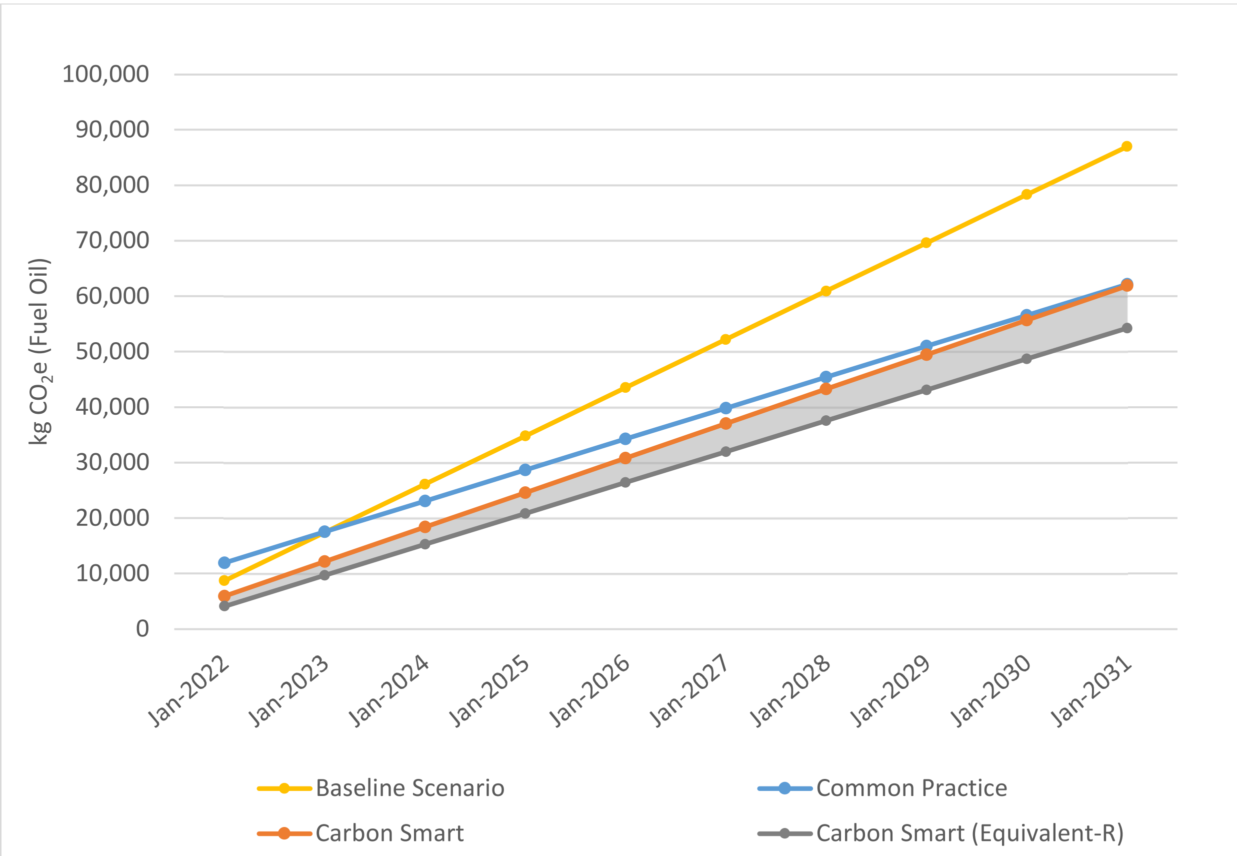

Figure 6. Kilograms of operational and embodied CO_2e emissions over time, for all measures.

Operational and embodied carbon emissions of the Carbon Smart and Carbon Smart (Equivalent-R) scenarios are lower than the Common Practice and Baseline scenarios beginning in the first year.

The Common Practice scenario has greater carbon emissions (operational and embodied) in the first year, relative to the Baseline, due to the embodied carbon impact of the weatherization materials. The carbon emissions (operational and embodied) of the Common Practice scenario are equalized with the operational emissions of the Baseline scenario in the second year due to the improved performance of the weatherized building.

The Common Practice and Carbon Smart emissions are nearly equivalent after approximately 10 years, with the higher embodied carbon emissions associated with Common Practice eventually being offset by its slightly better performance (due to space constraints in existing building cavities and a higher R-value per inch).

The carbon emissions (embodied and operational) of the Common Practice and Carbon Smart scenarios over 10 years are 15% higher than those of the Carbon Smart (Equivalent-R) scenario.

The Carbon Smart (Equivalent-R) scenario continues to have a more favorable carbon impact indefinitely, and notwithstanding the constraints of the existing assembly as described in the Modeling Assumptions section.

A choice not to weatherize the home at all would yield operational emissions over 10 years that are more than 60% greater the embodied and operational emissions of the Carbon Smart (Equivalent-R) scenario over the same 10-year period.

Additionally, strategies to achieve the Equivalent-R performance should not include materials with high embodied carbon emissions that compromise the carbon impact benefit represented by the shaded zone in Figure 6.

Conclusions

It has been accepted for quite some time that energy efficiency, and specifically weatherization, plays a central role in climate strategies for decarbonization. Less widely accepted, however, is the connection between this operational energy benefit and the impacts of both weatherization material choices and climate justice and equity issues within our communities.

In this study, the authors have illustrated how employing lower embodied carbon materials for weatherization work can offer greater emissions reductions (embodied and operational) beyond both a Baseline, "do-nothing" Scenario and a Common Practice scenario.

Material Choices, Carbon Impact and Time

Understanding the embodied carbon emissions impact of specific material choices for weatherization work is not only of critical importance now, but will continue to grow in importance as systems, appliances, and the electric grid become more efficient and continue to decarbonize. That is, decreases in future operating emissions realized through fuel switching and grid decarbonization will impact the expected time frame in which operational emissions savings will offset initial embodied emissions.

For this reason, considering the "Time Value of Carbon" (Strain 2020) and looking at both first-year impacts and impacts over time is important, as immediate emissions impacts hold critical value in addition to the longer-term benefits of annual operating emissions reduction. And while it is true that the Carbon Smart emissions for each of these practices is nearly equivalent to that of the Common Practice scenario by year 10, the significant plume of emissions at the beginning of the project saddles the project with an emissions debt. Given the very short time frame available for reducing the building sector's carbon emissions (Masson-

Delmotte et al. 2021) and the persistent impact of emissions in the atmosphere, emissions reduced immediately are of greater benefit than an equivalent reduction in the future.

The Carbon Smart (Equivalent-R) is the most favorable approach notwithstanding constraints of existing home building assemblies, but the Carbon Smart strategy offers a pathway to significant CO_2e reductions in the short-term with comparable long-term emission reductions when compared to the Common Practice. Furthermore, these short-term, first year emissions reductions are even more critically important when considered alongside the embodied carbon emissions that are avoided due to the reuse of an existing structure. The need to weatherize existing buildings in the shortest time to avoid irreversible climate change and to keep global average temperatures from rising more than 2°C is urgent.

Relative Impact of HFC-type vs. HFO-type Closed Cell Spray Foam

As shown in Figure 6, the carbon emissions (operational and embodied) of a weatherized typical Vermont home, employing Common Practice efforts, is equalized to those of an unimproved home in just two years. This conclusion, however, only applies to the use of HFO-type closed-cell spray foam. If HFC-type closed-cell spray foam products were used instead, the up-front embodied carbon emissions would be nearly 2.5 times higher in the first year and averaging just over 1.5 times higher each year for 10 years, when compared to the Common Practice approach employing HFO-type foam. Therefore, using HFC-type closed-cell spray foam in lieu of HFO-type foam adjusts the threshold of equalized carbon emissions, relative to baseline, from 2 years (for the HFO) to 7.5 years for an approach employing HFC-type foam[7]. When a Common Practice approach employing HFC-type closed-cell spray foam is compared to the Carbon Smart scenario the threshold for equalized carbon emissions is 37 years. This highlights the importance of avoiding high embodied carbon materials, especially HFC-type closed-cell spray foam, and instead selecting lower embodied carbon materials.

Vulnerabilities, Equity Opportunities, and Potential Benefits

Weatherization work can begin to address some of the climate justice inequities that are often most deeply felt by households that dedicate a greater percentage of their income to energy and utility costs. This benefit is even more relevant and increasingly significant when considered in conjunction with opportunities to reduce the first costs/capital costs for weatherization through incentives especially when weighed against the rising cost of new construction and the associated dramatic embodied carbon emissions impact of new construction.

Additionally, weatherized buildings that employ good building science have the potential to improve occupant comfort and health through reduced drafts and the avoidance of mold/moisture concerns which also offer the benefit of enhanced building durability, thereby potentially reducing or avoiding medical costs for chronic conditions and avoiding or deferring building maintenance costs. These benefits are much more difficult to quantify, but can have a dramatic effect especially for the most vulnerable members of our communities.

[7] See Table 1. Global warming potential (GWP) of insulation material and R-value summary.

Furthermore, history has shown that it is often our most vulnerable and marginalized communities that suffer the greatest challenges and losses as a result of climate change associated catastrophic events like flooding, excess heat and cold, etc.

Decarbonization at Scale

Although the authors do not directly address the topic, this research has a significant implication for new construction. The impact of embodied carbon emissions of insulation materials in the short term (year one) highlights the impact that material emissions can have on a building's carbon emissions profile. Considering the substantial embodied carbon emissions for a new construction project (comprehensively, not just limited to insulation and weatherization materials), it becomes apparent from a carbon standpoint that investing to weatherize existing buildings to reduce their operational emissions is preferable to demolition and rebuild on a site.

If 36 "typical Vermont Homes" were weatherized this year employing the Common Practice or the Carbon Smart scenarios described herein, in 10 years the equivalent emissions reduction would be similar to that of not burning approximately 1 million pounds of coal or driving an average passenger vehicle nearly 200,000 miles annually (EPA 2020). It would require only 27 homes to achieve the same result if the Carbon Smart (Equivalent-R) scenario was employed instead.

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