Embodied and Operational Emissions in Retrofitting Vermont Homes

EFFICIENCY VERMONT R&D PROJECT

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Megan Nedzinski—Vermont Integrated Architecture, PC
Jacob Deva Racusin—New Frameworks
Leslie Badger, Chris Gordon, Brian Just—Efficiency Vermont

Efficiency Vermont
20 Winooski Falls Way
Winooski, VT 05404

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Executive Summary

The carbon impact of weatherization work is affected not only by decreased energy use from insulation and air sealing upgrades, but also by the embodied carbon emissions of the materials used, which are primarily released prior to the realization of any operational emission savings. A comparison is made between one of the most common insulation practices in Vermont's Home Performance with ENERGY STAR® program (closed cell spray foam), herein referred to as "Common Practice," and readily available and cost competitive "Carbon Smart" insulation practices (dense pack cellulose and polyisocyanurate) to evaluate the carbon impact of weatherization materials choices both in the first year and over time.

The Carbon Smart approach employs dense pack cellulose and polyisocyanurate instead of spray foam insulation offering a pathway to significant CO_2e reductions in the short-term (first 1-2 years). Furthermore, the carbon emissions (operational and embodied) of the Common Practice and Carbon Smart scenarios are equivalent after approximately 10 years, with the higher embodied carbon emissions associated with Common Practice eventually being offset by its slightly better operational performance. ("Common Practice" spray foam is often used in weatherization projects due to space constraints in existing building cavities because it has a higher R-value per inch.) A third scenario, Carbon Smart (Equivalent-R), was also evaluated and found to have a more favorable carbon impact indefinitely when there is a comparable installed R-value to Common Practice using Carbon Smart materials. In addition, all three weatherization scenarios are compared to emissions of a baseline condition of a typical Vermont home undergoing no weatherization work.

This white paper provides additional data and details to a paper originally published in the ACEEE proceedings from the 2022 Summer Study on Energy Efficiency in Buildings.[1]

Introduction

As awareness grows that buildings are a part of the climate change solution, more homeowners and building professionals want to know how to reduce greenhouse gas emissions associated with home weatherization projects. This study builds on a 2020 greenhouse gas retrofit study[2] focused on the embodied carbon impact of insulation materials commonly used in weatherization. In this study, the authors leverage their prior findings to assess the carbon impact of weatherization material choices while also

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[1] Nedzinski, Megan, Jacob Deva Racusin, Leslie Badger, Chris Gordon, and Brian Just, "The Climate Impact of Retrofits: Embodied and Operational Emissions in Weatherization," Proceedings of the American Council for an Energy-Efficient Economy Summer Study, 2022. https://aceee2022.conferencespot.org/event-data/pdf/catalyst_activity_32335/catalyst_activity_paper_20220810190435199_5069570b_4520_4b72_88b1_e385225bd864.

[2] Nedzinski, Megan, Jacob Deva Racusin, Chris Gordon, Brian Just, Matt Sharpe, and Mike Fink, "Embodied Carbon in Vermont Residential Retrofits," Efficiency Vermont R&D Program Report, 2020. https://www.efficiencyvermont.com/news-blog/whitepapers/embodied-carbon-in-vermont-residential-retrofits.

accounting for reduced operational carbon emissions associated with the decreased energy use resulting from weatherization upgrades. Efficiency Vermont Home Performance with ENERGY STAR® (HPwES) program data and the Vermont Department of Public Service's Vermont Single-Family Existing Homes Overall Report[3] and supporting data provide a basis for the most common insulation practices, which are then compared with a home using low-carbon insulation practices. Comparing the carbon emissions[4] for specific applications can inform material choices at the outset of a project and optimize carbon emissions over time.

Research Tasks

This study encompasses the following tasks:

1) Calculate the approximate operational carbon savings when a typical existing Vermont home is weatherized using the most commonly adopted HPwES practices.[5]

2) Calculate the carbon impact (operational and embodied carbon of materials) for the first year of implementation when a typical Vermont home is weatherized:
    a. Using the most commonly adopted HPwES practices ("Common Practice").
    b. Using lower-carbon approaches with HPwES practices ("Carbon Smart").

3) Calculate the time period required to equalize the up-front embodied carbon emissions for specific installed weatherization practices with the estimated operational carbon emissions avoided:
    a. Using the most commonly adopted HPwES practices ("Common Practice").
    b. Using lower-carbon approaches with HPwES practices ("Carbon Smart").

Methods

Definitions

This study defines the following terms:

I. *Materials:* Insulation types used for any of the various applications. The following materials were included in this study:
    a. Cellulose, dense pack
    b. Polyisocyanurate (polyiso), rigid board (foil-faced)

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[3] NMR Group, Inc. "Vermont Single-Family Existing Homes Overall Report," Vermont Department of Public Service, 2019. https://publicservice.vermont.gov/sites/dps/files/documents/VT%20SF%20Existing%20Homes%20Overall%20Report%20-%20FINAL%20022719.pdf.

[4] Reference "Definitions" section under Methods

[5] As determined from Efficiency Vermont Home Performance with ENERGY STAR data and the "Vermont Single-Family Existing Homes Overall Report" source data.

    c. Spray polyurethane foam (SPF), closed-cell (hydrofluoroolefin [HFO] blowing agent)

II. *Applications:* The physical space in a building in which a practice has been applied. The following applications were included in this study:

    a. Basement wall
    b. Basement rim joist
    c. Wood-framed wall
    d. Closed cavity ceiling

III. *Practices and measures:* Installed insulation materials at defined R-values based on a "typical Vermont home" construction for each physical application.

IV. *A typical Vermont home:* Drawing from the Efficiency Vermont 2012–2016 Home Performance with ENERGY STAR data set and the 2016 Vermont Department of Public Service's Report, a two-story, three-bedroom, single-family residence of approximately 2,200 square feet located in Vermont. See Appendix A: Modeling Inputs Summary Matrix for detailed information regarding construction assembly and system assumptions and the associated data source for each "Baseline" and "Common Practice" assumption.

V. *R-value*: A material's resistance to conductive heat flow, measured or rated in terms of its thermal resistance. The higher the R-value, the greater the effectiveness of the insulation.[6] R-values for materials are expressed as the R-value per inch of material. See Table 1 below. Note that effective assembly R-values were modeled, taking into account common framing characteristics; nominal insulation values; and insulation installation grade for Baseline, Common Practice, and Carbon Smart scenarios (see the Approach and the Modeling Assumptions for Compared Scenarios sections for more details).

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

Material	Form or variant	R-value/ inch	GWP average* kg CO_2e *[A1-A3 w / A5+B1]* per m^2 RSI-1	GWP components[8]
Cellulose	Dense pack, 3.55 pcf	3.56	-2.16	A1-A3, A5, B1 carbon storage

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[6] For more information about insulation and the role of R-values, and a zone map of states' and counties' respective insulation needs, see the U.S. Department of Energy's web page on insulation: https://www.energy.gov/energysaver/weatherize/insulation.

[7] Brian Just. "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 Program Report, 2020. https://www.efficiencyvermont.com/news-blog/whitepapers/the-high-greenhouse-as-price-tag-on-residential-building-materials.

[8] For explanation of GWP components, see Figure 1 below

Polyisocyanurate	Board, foil-faced	6.53	2.32	A1-A3; A5, B1 not given
Spray polyurethane foam (SPF)	Spray, closed-cell hydrofluorocarbons (HFC)[9]	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[10]	Siliconized Acrylic Sealant	N/A	1.7	A1-A3

* Averages used in this study are based on 100-year GWP value and appear in highlighted column.

V. *Improved R-values*: The total R-value of the application as a result of the installed practice.

VI. *Carbon, C:* The element carbon, as present in both atmospheric carbon dioxide (CO_2) molecules and as an element in biogenic materials such as those made of wood. The mass of carbon is valued in biogenic materials to determine an equivalent CO_2 mass that has been drawn down through photosynthesis into a plant, representing a negative emission (see Approach 3.2 below). *Carbon* is also used herein as a "shorthand" reference for *carbon dioxide equivalent* in the context of describing greenhouse gas emissions.

VII. *Carbon dioxide, CO_2:* The atmospheric molecule that is a primary greenhouse gas contributing to climate change; CO_2 emissions, among other greenhouse gases, are released in the production of materials and energy used in buildings.

VIII. *Carbon dioxide equivalent, CO_2e:* The metric used to value the global warming potential (GWP) of a material, fuel, or building; the GWPs of all emitted greenhouse gases are reported in their equivalent impact over time as CO_2. For example, methane has a 100-year GWP approximately 25 times that of CO_2; therefore, a kilogram (kg) of methane has a GWP of 25 kg CO_2e. All GWP's used in this analysis are based on a 100-year timeframe.

IX. *Stored carbon:* The amount of carbon stored in the mass of a biogenic material, generally expressed in CO_2e in the context of GWP. The term *stored* is used rather than *sequestered*, indicating that the carbon present in this material may be burned, decomposed, or otherwise reintroduced to the carbon cycle as a CO_2e emission at the end of the building's life cycle. The decision of whether to value the carbon

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[9] 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.

[10] 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

storage of a given biogenic material can be very complex. In the case of cellulose insulation (the only material in the study featuring a significant percentage of biogenic material), the source of this material is predominantly recycled paper and cardboard diverted from the waste stream, and therefore the authors hold confidence in the valuation of carbon storage for this material.

X. *Carbon emissions:* The embodied carbon emissions associated with weatherization materials *combined with* the operational carbon emissions resulting from building use. *Carbon emissions* is used herein as a "shorthand" referring to the combined carbon impact of these two factors together. In cases where either of the two contributing factors (i.e., embodied carbon emissions and operational carbon emissions/savings) are referenced independently, it is explicitly noted as such.

XI. *Embodied carbon emissions:* Greenhouse gas emissions that result from the extraction, processing, manufacturing, transportation, and installation of building materials, as well as emissions released during use (excluding operational use of the building) and end-of-life scenarios. The focus of this study is on "up front" embodied carbon emissions beginning with material extraction through installation, whereas a more comprehensive definition of embodied carbon may include emissions released throughout the entire life span of the material. Specifically, the study team used the 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]). However, other emissions during those phases such as worker and material transportation to site were not included in this study. Note that 10 years (the time boundary of this study) of 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. Stored carbon, discussed above, was also accounted for in cellulose installations as a negative emission in equivalent mass of CO_2. The team applied the global warming potential (GWP) emissions factor, expressed as kilograms of CO_2e, for each material based on averages derived from Environmental Product Declaration (EPD) data. See Figure 1 for more detail on life cycle assessment product stages.

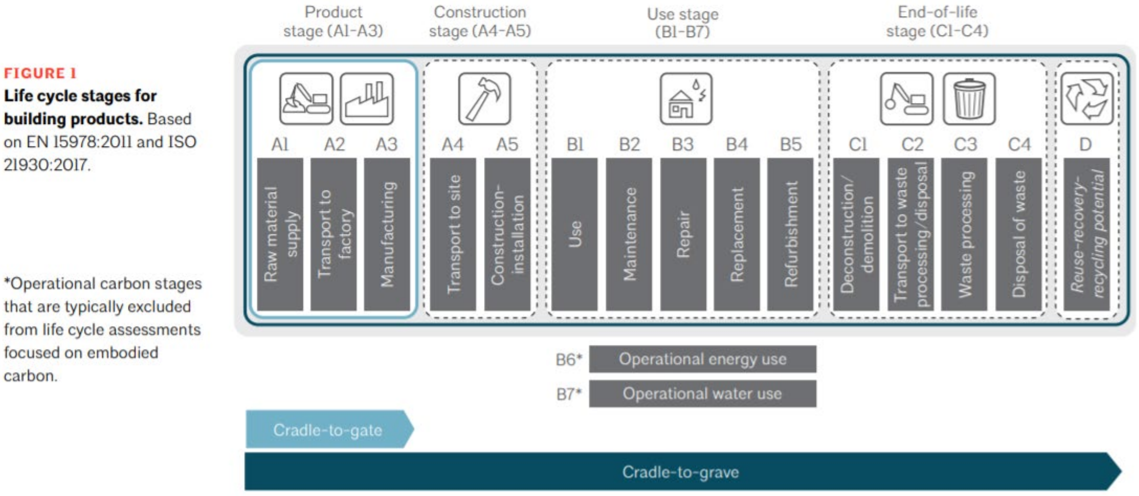

Figure 1: Life cycles stages for building products[11]

XII. *Operational carbon emissions:* The CO2e associated with fuel use in a home or building. The operational emissions of the building include fuel and electricity used to provide heating, cooling, lighting, domestic hot water, plug load, and other energy-consuming services to the building during its operation. These emissions are separate from the embodied carbon emissions associated with material consumption over the life cycle of the building.

Approach

1. An OpenStudio (OS) energy model was created in the OS Parametric Analysis Tool (PAT). Building characteristics such as total conditioned square feet, assembly R-values, and mechanical system efficiencies were entered into PAT. The PAT generates an HPXML building description file that is converted to an OS model. An EnergyPlus hourly simulation was performed on the OS energy model. Simulations were run for each component and variable efficiency value for each application and scenario.
    1.1. The results focus on gallons (gal) of fuel oil reduction resulting from weatherization upgrades.

    1.2. The impact of kilowatt-hours (kWh) usage for non-heating energy was excluded from this analysis as no other system or building changes were made (i.e., there was no change in fenestration, mechanical equipment, building configuration, lighting, assumed plug loads, etc.)

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[11] Meghan Lewis, Monica Huang, Stephanie Carlisle, Kate Simonen, "AIA-CLF Embodied Carbon Toolkit for Architects, Part II: Measuring Embodied Carbon," 2021. https://content.aia.org/sites/default/files/2021-10/21_10_STN_DesignHealth_474805_Embodied_Carbon_Guide_Part2.pdf

2. kg CO_2e reduction was calculated for each measure or measure combination over the Baseline.
    2.1. Gallons of oil were converted to kg CO_2 per EPA calculations and references using the following conversion: *The average carbon dioxide coefficient of distillate fuel oil is 430.80 kg CO_2 per 42-gallon barrel (EPA 2020).*[12]

    2.2. The team calculated the quantity of material / type of insulation used in each project application (see Modeling Assumptions section below for additional detail), from the number of inches of material for each type of insulation installed.

3. The team calculated embodied carbon emission values, by project application, using 2020 EPD data compiled by Brian Just of VEIC.[13] All measures assume HFO-type closed-cell SPF for Common Practice scenarios, and dense pack cellulose for Carbon Smart scenarios, with the exception of foundation walls, which assumes foil-faced polyiso for the Carbon Smart scenarios. The authors included foil-faced polyiso board insulation in the Carbon Smart foundation wall scenario because it is a material that is commonly available and installation context is similar to that of the Common Practice scenario. Although alternative strategies exist for insulating foundation walls with less carbon intensive materials (e.g., wood fiberboard and cellulose), those strategies require additional moisture and installation considerations and risk, and therefore are not as commonly implemented.
    3.1. Although Efficiency Vermont's HERO[14] (Home Energy Reporting Online) data set does not specify the type of the SPF product used, for the purposes of this study the team used the GWP value of HFO-type closed-cell SPF insulation in order to reflect the expected near-term phaseout of the more carbon intensive HFC-based products.[15]

    3.2. The team assigned carbon storage values to bio-based materials as an expression of the carbon dioxide removed from the atmosphere and photosynthesized into biogenic carbon present in the material[16]. To quantify this value, the team determined the percentage of biologic content in the material from the product EPD and applied it to the weight of the material to determine the mass of biologic content in the material. This value was then multiplied by the percentage of carbon present in this biologic content as

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[12] Environmental Protection Agency. "Greenhouse Gases Equivalencies Calculator—Calculations and References," 2020. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references.

[13] Just, "The high greenhouse gas price tag on residential building materials: True life cycle costs (and what can be done about them)."

[14] For HERO explanation, see "Modeling Assumptions" below.

[15] Reference State of Vermont's Act 65: An Act Relating to the Regulation of Hydrofluorocarbons, 2019. https://legislature.vermont.gov/Documents/2020/Docs/ACTS/ACT065/ACT065%20As%20Enacted.pdf.

[16] See Definitions for additional discussion regarding carbon storage calculations for biogenic materials.

defined in the Phyllis database[17] to determine the mass of carbon present in the material per functional unit. That value was then multiplied by 3.67, which is the ratio of the molar mass of carbon dioxide (44) to the molar mass of carbon (12), to equate to carbon dioxide equivalent (CO_2e). The resulting value is the kg CO_2e stored in the material, expressed as a negative value (i.e., emissions reduced from the atmosphere).

4. The team determined carbon impact:
    - 4.1. Research Task 1 – Operational emissions
        - 4.1.1. Annual/first year energy model results were graphed to illustrate operational carbon emissions of the Baseline "do nothing" scenario alongside each of the weatherized scenarios
        - 4.1.2. Annual/first year energy model results were also graphed for each measure individually, and all measures combined to illustrate operational carbon emissions *saved* relative to the Baseline.
    - 4.2. Research Task 2 – First year carbon impact (embodied and operational)
        - 4.2.1. Calculated as: embodied carbon emissions + annual/first year operational carbon emissions (modeled).
        - 4.2.2. This was calculated for each scenario compared to the Baseline scenario, and for each weatherization measure individually.
    - 4.3. Research Task 3 - Carbon impact (embodied and operational) over time
        - 4.3.1. Calculated as: embodied carbon emissions + annual/first year operational carbon emissions (modeled) + (annual operational carbon emissions [modeled] x number of years)
        - 4.3.2. This was calculated for each scenario compared to the Baseline scenario, and for each weatherization measure individually.

Modeling Assumptions

1) *"Baseline" and "Common Practice":* 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 HERO tool. The study team sorted the data[18] to identify only the completed projects with installed measures, excluding entries listed as "recommendations." 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."[19] Additionally, where HERO

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[17] EU 7th Framework Programme. Phyllis2, 2021. https://phyllis.nl/Browse/Standard/ECN-Phyllis.

[18] 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).

[19] NMR Group, Inc. "Vermont Single-Family Existing Homes Overall Report" and supporting data. https://publicservice.vermont.gov/sites/dps/files/documents/VT%20SF%20Existing%20Homes%20Overall%20Report%20-%20FINAL%20022719.pdf.

data were lacking or insufficient to establish Baseline and Common Practice data for inclusion in the OpenStudio model, the team used the Vermont Department of Public Service's "Vermont Single-Family Existing Homes Overall Report" as a data source. Examples of building characteristic values obtained from the report are conditioned floor area, heating system type, and window assumptions. See Appendix A: Modeling Inputs Summary Matrix for additional information regarding each modeling input and the data origin.

2) *"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 Department of Public Service's "Vermont Single-Family Existing Homes Overall Report," which confirmed each assumption to be reasonable. 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. See Appendix A: Modeling Inputs Summary Matrix for additional information.

3) *"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. See Appendix A: Modeling Inputs Summary Matrix for additional information. See also item 4 below.

4) *Embodied carbon impacts of materials:* In each of the weatherization scenarios, the embodied carbon impact associated with the insulation and air-sealing materials used was included in the analysis. See Table 1.
    a) The additional embodied carbon impacts for the removal and replacement of finishes, added strapping, or other means of providing access or increasing framing depths were not included in any of the scenarios.
        i) In the *"Carbon Smart (Equivalent-R)"* scenario the embodied carbon emissions for the additional weatherization materials were included, however the additional embodied carbon emissions that would be required to increase the cavity depth were not.

b) For the Carbon Smart and Carbon Smart (Equivalent-R) scenarios, the air-infiltration improvement was assumed to be achieved using caulk. The embodied carbon value per linear foot of caulk was included in the calculations of these scenarios. The team used the following interpretations and calculations as the basis of these assumptions:
    i) Linear footage of air-sealing caulking was calculated as follows:
        (1) Band joist = 3x linear footage of building perimeter, which assumes caulking at the following locations:
            (a) Mudsill to concrete
            (b) Mudsill to band joist
            (c) Band joist to subfloor
        (2) Foundation = none
            (a) This area is assumed to be below grade incorporating a monolithic poured concrete or mortared block wall, therefore assumed to have negligible air leakage
        (3) Walls = 3x linear footage of building perimeter
            (a) Assumes that some air sealing is performed at windows, doors, and mechanical and electrical penetrations of exterior walls, as well as transitions to other building assemblies
        (4) Closed cavity ceiling = 3x linear footage of building perimeter
            (a) Assumes that some air sealing is performed at mechanical and electrical (e.g., lighting) penetrations of ceiling planes, as well as transitions to walls and between ceiling planes.

5) *Air infiltration:* The existing air infiltration rate was assumed to be 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 where blower door values were provided. The data set was filtered to this size range to better represent the “typical” Vermont existing home size of 2,200 square feet used for modeling. The team also obtained average air leakage reduction post-weatherization from the HERO data set and assumed to be 30%, or 8.4 ACH50. The 30% air-infiltration improvement associated with all measures was further broken down and allocated to each of the various weatherization practices because some weatherization practices have greater potential for improvement than others. Data obtained from HERO indicated that the average air leakage reduction associated with band joist insulation was 17%. In order to determine the breakdown of the remaining 13% air-infiltration improvement (30% minus 17%) associated with wall and ceiling measures, the team compared the total treated area of each weatherization practice with the overall area of the building and air-infiltration

potential for improvement. The following interpretations and calculations were the basis of these assumptions:

- a) Wall / ceiling ratio was calculated as follows:
    - i) 2,160 sf wall area = ((40'*2)+(27.5'*2))*2*8'
    - ii) 1,232 sf ceiling area = (1100*1.12 area multiplier for 6:12 roof pitch)
    - iii) Wall area ratio of 64% = (2,160 sf wall area)/(2,160 sf wall area + 1,232 sf ceiling area)
    - iv) Ceiling area ratio of 36% = (1,232 sf ceiling area)/(2,160 sf wall area + 1,232 sf ceiling area)

- b) Allocation of the 30% total air-infiltration improvement broken down by measure:
    - i) 12.0 ACH50: Baseline
    - ii) 12.0 ACH50: Basement, w/ 0% air leakage reduction
        - (1) This area is assumed to be below grade through solid poured concrete or mortared block walls, therefore assumed to have negligible air leakage
    - iii) 10.0 ACH50: Band joist, with 17% air leakage reduction
    - iv) 11.0 ACH50: Wall, with 8.3% air leakage reduction
        - (1) Total improvement (30%) less band joist improvement (17%) = 13%
        - (2) Wall area is 64% of total building area, therefore 64% of 13% = 8.3% reduction
    - v) 11.4 ACH50: Closed cavity ceiling, with 4.7% air leakage reduction
        - (1) Total improvement (30%) less band joist improvement (17%) = 13%
        - (2) Ceiling area is 36% of total building area, therefore 36% of 13% = 4.7% reduction
    - vi) 8.4 ACH50: Whole house (cumulative of the above), w/ 30% air leakage reduction

6) *Energy model verification:* To verify modeled energy usage against a data set of measured energy usage, the authors referenced a 2020 study released by the State of Wisconsin[20] evaluating energy consumption of projects in its weatherization program, since such a study was not available from a Vermont data set. Given a comparable heating climate, this study provides a point of reference for the accuracy of this study's modeled data.

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[20] Andy Lick, Maddie Koolbeck, Scott Pigg, and Robert Parkhurst of Slipstream. "Assessment of Energy and Cost Savings for Homes Treated under Wisconsin's Home Energy Plus Weatherization Program," Wisconsin Department of Administration: Division of Energy, Housing, and Community Resources, 2020.

In the Wisconsin study, metered heating fuel data were collected and analyzed for approximately 4,000 single-family homes in 2019. An average 17% reduction in heating fuel was measured for single-family homes as a result of weatherization efforts in the study. Baseline average pre-weatherization fuel usage of approximately 975 therms of natural gas, or 97,500 kBtu,[21] was reported, which yielded an average post-weatherization fuel usage of 80,925 kBtu. The modeled baseline energy use in the Vermont study is 118,297 kBtu, which would account for a deviation of approximately 21% between the Wisconsin study results and the Vermont modeled baseline value. The Vermont team's modeled energy use of all Common Practice improvements is 75,844 kBtu, which would account for a deviation of approximately 7% between the Wisconsin study results and the Vermont team's modeled improvement value.

The Vermont analysis shows a modeled energy reduction of 36%, slightly higher than the Wisconsin study's 'highest energy user' results. The "typical Vermont home" Baseline, comprised of 2x4 above grade walls and only sloped ceilings, is more representative of the highest energy user in the Wisconsin study. Additionally, the authors expect that the insulation and air-sealing improvements modeled in this study, based on HPwES projects, exceed the improvement measures conducted in the Wisconsin study. For these reasons, the authors believe that the modeled results are reasonable in comparison to the Wisconsin measured data.

While the authors recognize there is some deviation of modeled results from the measured energy usage and reduction, the team believes these deviations fall within expected margins of error for average annual energy modeling of large data sets and are confident 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[22] and that median absolute modeled to measured heating energy use varies from 24% to 37% for commonly used residential modeling tools[23] .

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[21] U.S. Energy Information Administration, 2021. https://www.eia.gov/tools/faqs/faq.php?id=45&t=8,

[22] Glickman, J. 2014. "Home Energy Score Analysis Report." Washington, DC: U.S. Department of Energy. betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/Home%20Energy%20Score%20Analysis%20Summary%20Report%20May%202014%20Update_Final.pdf.

[23] Roberts D., N. Merket, B. Polly, M. Heaney, S. Casey, and J. Robertson. 2012. "Assessment of the U.S. Department of Energy's Home Energy Scoring Tool." Golden, CO: National Renewable Energy Laboratory. www.nrel.gov/docs/fy12osti/54074.pdf.

Results and Analysis

The results of this study are as follows:

***Research Task 1:** Calculate the approximate operational carbon savings when a typical existing Vermont home is weatherized using the most commonly adopted HPwES practices.*

Figure 2 illustrates the first year of operational carbon emissions for each of the modeled scenarios as well as a Baseline scenario. In the Baseline "do nothing" scenario no weatherization improvements were made.

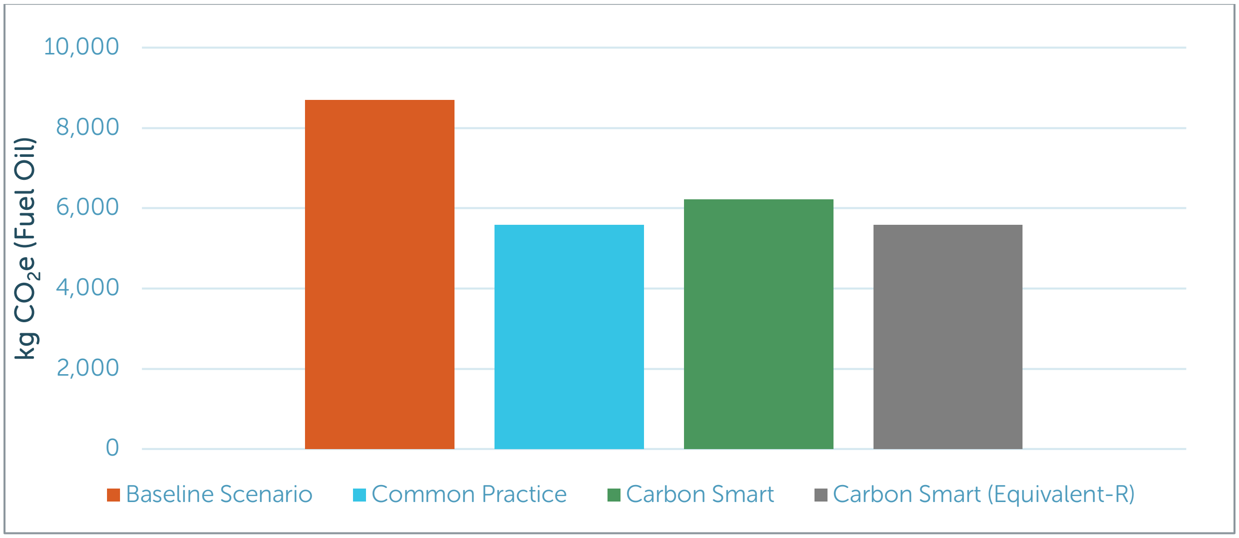

Figure 2: First-year operational kg CO2e emissions—all measures

Figure 3 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 CO_2e difference between the Common Practice and Smart Carbon 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.[24] 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.

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[24] U.S. Environmental Protection Agency. Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

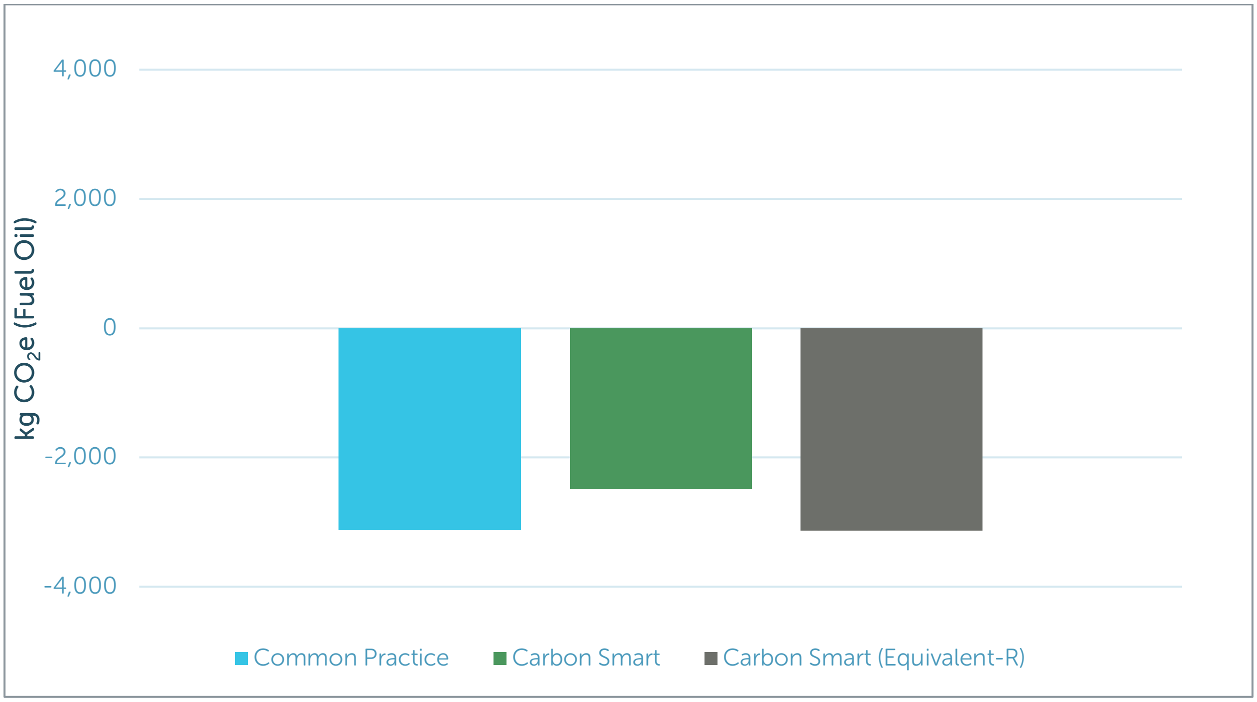

Figure 3: First-year operational kg CO2e savings compared to baseline condition—all measures

Figure 4 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.

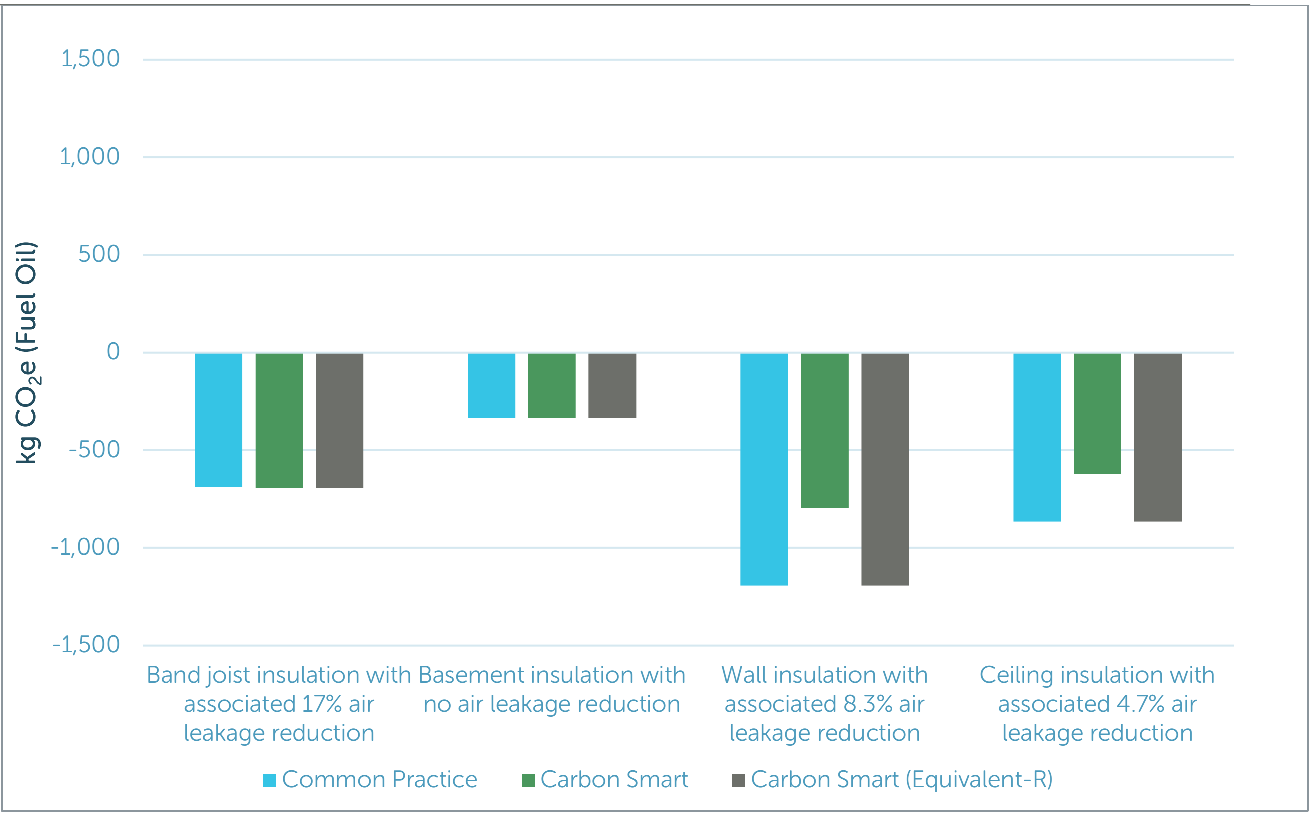

Figure 4: First-year operational kg CO2e savings by measure compared to baseline condition

See Appendix B: Operational Emissions Savings of Compared Scenarios Over Time for an illustration of these results over a 10-year period.

Research Task 2: Calculate the carbon impact (operational and embodied carbon) for the first year of implementation when a typical Vermont home is weatherized using the most commonly adopted HPwES practices and using low-carbon materials and approaches.

Figure 5 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.

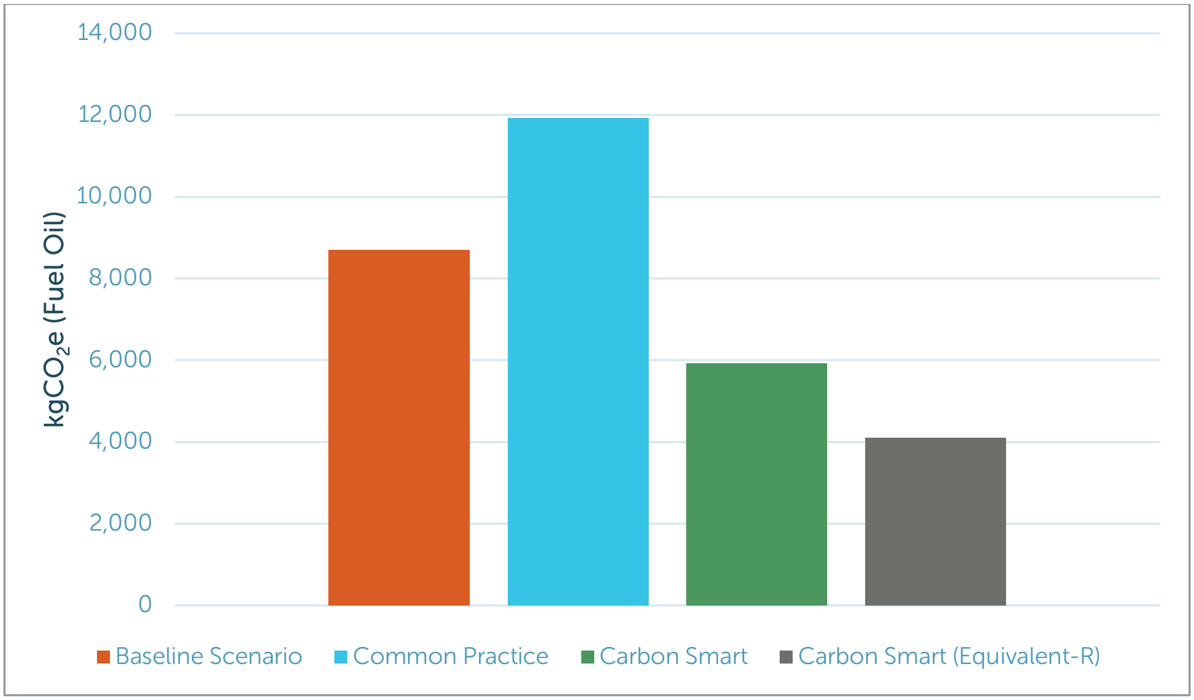

Figure 5: First-year kg CO2e emissions (operational and embodied)—all measures

Figure 6 breaks down the results shown in Figure 5 to illustrate the carbon emissions (embodied and operational) by measure for each of the various weatherization scenarios.

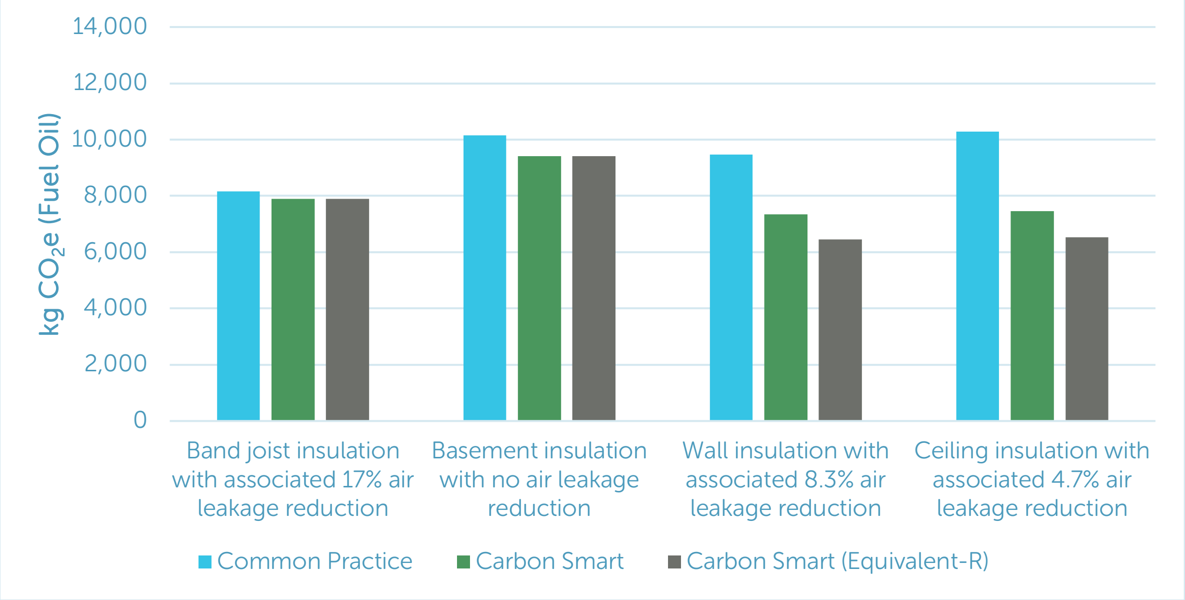

Figure 6: First-year kg CO2e carbon emissions (operational and embodied) by measure

Research Task 3: Calculate the time period required to equalize the up-front embodied carbon emissions for specific installed weatherization practices with the estimated operational carbon emissions avoided using the most commonly adopted HPwES practices and using low-carbon materials and approaches.

Figure 7 illustrates the embodied carbon emissions of the weatherization materials employed at all applications and their associated operational carbon emissions over time. For more detail and supporting graphics for individual measures, refer to Appendix C.

The carbon emissions (operational and embodied) 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 Smart (Equivalent-R) scenario continues to have a more favorable carbon impact indefinitely. As noted in the Modeling Assumptions section, the additional embodied carbon impacts for the removal and replacement of finishes, added strapping, or other means of providing access or increasing framing depths were not included in any of the scenarios. The embodied carbon emissions for the additional weatherization materials were included, however the additional embodied carbon emissions that would be required to increase the cavity depth were not. Therefore, 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 yellow zone in Figure 7.

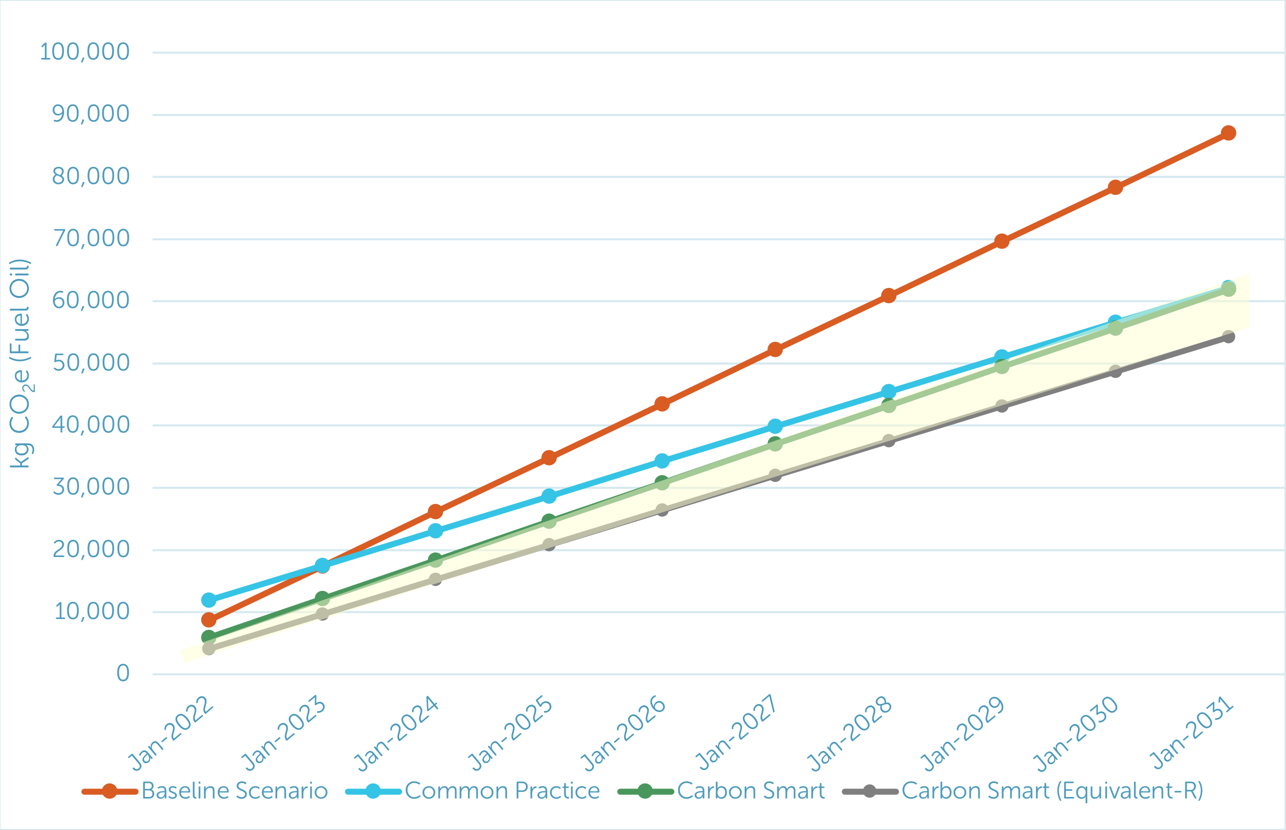

Figure 7: kg CO2e emissions (operational and embodied) over time - all measures

It is important to note the "Time Value of Carbon"[25] as it relates to the findings illustrated in Figure 7. Although 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, these materials release a significant plume of emissions at the beginning of the project, saddling the project with an emissions debt. Given the very short time frame available for reducing the building sector's carbon emissions[26] and the persistent impact of emissions in the atmosphere, emissions reduced immediately are of greater benefit than an equivalent reduction in the future. It is also worth noting that decreases in future operating emissions 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, 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.

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[25] For additional information, see Larry Strain's white paper developed for the Carbon Leadership Forum titled "The Time Value of Carbon." https://carbonleadershipforum.org/the-time-value-of-carbon/.

[26] V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.). IPCC. "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." Cambridge University Press. In press.

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.

Conclusions

It has been accepted for quite some time that weatherization work is important for reducing operational carbon emissions. As the authors concluded in their 2020 study, understanding the embodied carbon emissions of weatherization work is also of critical importance. 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 the Common Practice HPwES practices.

A typical Vermont home, when weatherized using Common Practice measures, in all four applications studied (band joist, basement, walls, ceiling), will yield higher carbon emissions (operational and embodied) in the first year than practices employing lower embodied carbon materials or by leaving the building as-is (i.e., Baseline). In the first year, the Common Practice scenario will represent approximately a 50% *increase* in carbon emissions over the Baseline, "do-nothing," scenario, and approximately twice the emissions of the Carbon Smart scenario (Figure 5).

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 5). Wall and ceiling applications offer the greatest opportunity for emissions reductions in the first year if *low embodied carbon materials are used* (Figure 6).

Given the high rate of operational emissions for a typical Vermont home, conducting weatherization work is beneficial to reducing operational carbon emissions within a short time. 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 (Figure 7). This conclusion, however, only applies to the use of HFO-type closed-cell spray foam, as defined in Methods above; were HFC-type closed-cell spray foam products to be 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 ten 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. (Figure 8). This highlights the importance of avoiding high embodied carbon materials, especially HFC-type closed-cell spray foam, and instead selecting lower embodied carbon materials.

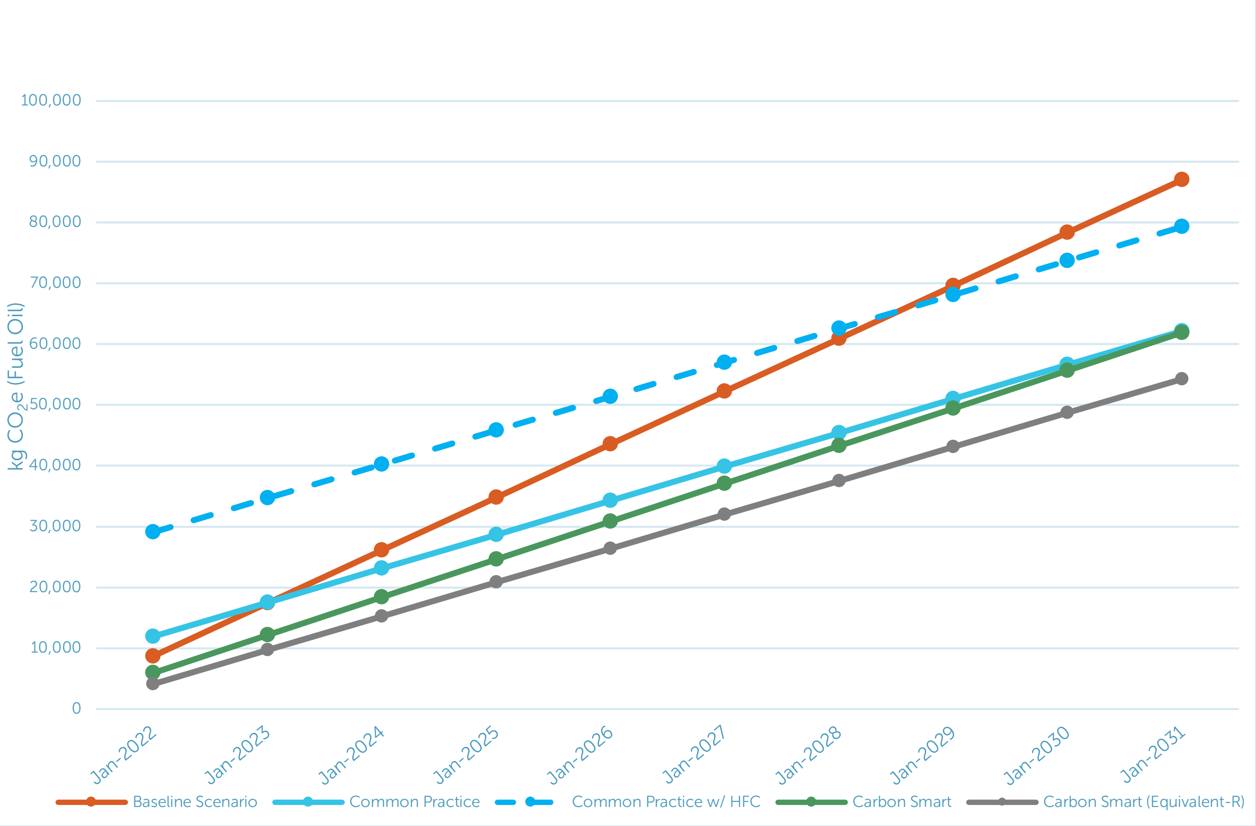

Figure 8: kg CO2e emissions (operational and embodied) over time - all measures; HFC foam included

Both the Carbon Smart and Carbon Smart (Equivalent-R) scenarios represent reduced carbon emissions (embodied and operational) in the first year due to the use of lower embodied carbon and carbon-storing materials. The Common Practice scenario, which employs higher R-value, and higher embodied carbon materials within the constraints of the existing framing cavities reaches parity with the Carbon Smart scenario after approximately 10 years.

- The carbon emissions (embodied and operational) of the Common Practice scenario over 10 years are 15% higher than those of the Carbon Smart (Equivalent-R) scenario
- A choice not to weatherize the home at all would yield operational emissions over 10 years that are more than 60% greater than the embodied and operational emissions of the Carbon Smart (Equivalent-R) scenario over the same 10-year period.

If 36 such houses were weatherized in Vermont this year employing the Common Practice or the Carbon Smart scenarios described here, in 10 years the equivalent emissions reduction would be similar to that of not burning approximately 1 million pounds of coal which is equivalent to driving a passenger vehicle approximately 200,000 miles annually.[27] It would require only 27 homes to achieve the same result if the Carbon Smart (Equivalent-R) scenario was employed instead.

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 quickly becomes apparent that investing to weatherize existing buildings to reduce their operational emissions, while avoiding the embodied carbon emissions of new construction, is critically important.

Appendices

A. Modeling Inputs Summary Matrix
B. Operational Emissions Savings of Compared Scenarios Over Time
C. Carbon Emissions (Embodied and Operational) Over Time by Measure

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[27] U.S. EPA. Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

Appendix A: Modeling Inputs Summary Matrix

The Modeling Inputs Summary Matrix displays modeling input values, data sources, and references.

Ref			MODEL INPUT VALUES			
			Existing Case	Common Practice	Carbon Smart	Carbon Smart (Equivalent R)
		General Building				
1	🟨	Size (sf)	2,200	2,200	2,200	2,200
2	🟨	Floors	2	2	2	2
3	🟨	Bedrooms	3	3	3	3
4		Wall height	8'	8'	8'	8'
5	🟨	Foundation type	Unconditioned basement	Unconditioned basement	Unconditioned basement	Unconditioned basement
6		**Envelope**				
7		**Floor**				
8		Framing	2x10, 16 o.c.	2x10, 16 o.c.	2x10, 16 o.c.	2x10, 16 o.c.
9	🟨	Insulation nominal R-value	R-0	R-0	R-0	R-0
		Rim joist				
		Height	10.75"	10.75"	10.75"	10.75"
10	🟨	Insulation nominal R-value	R-5.8	R-19.8	R-19.6	R-19.6
		Description		Assumes approx. 3" closed- cell foam	Assumes approx. 5.5" DP cellulose w/ caulking	Assumes approx. 5.5" DP cellulose w/ caulking
11		**Foundation**				
12	🟦	Wall type	Concrete (block or poured)	Concrete (block or poured)	Concrete (block or poured)	Concrete (block or poured)
13		Wall height	8'	8'	8'	8'
14	🟨	Insulation R-value	R-3.5	R-19.8	R-19.6	R-19.6
15	🟨	Description		Assumes approx. 3" of closed- cell SPF	Assumes 3" of polyiso	Assumes 3” of polyiso
		Insulation location	Inside	Inside	Inside	Inside
16		**Attic**				
17	🟨	Type	Closed cavity ceiling	Closed cavity ceiling	Closed cavity ceiling	Closed cavity ceiling

18	🟦	Framing	2x8, 16 o.c.	2x8, 16 o.c.	2x8, 16 o.c.	2x8, 16 o.c.
19	🟨	Insulation nominal R-value	R-9.9	R-39.6	R-18.7	R-39.2
	🟨	Assembly effective R-value	R-10.5	R-28.6	R-17.9	R-28.6
20	🟨	Description		Assumes 6" of closed-cell SPF (see reference 20)	Assumes 5.25" DP cellulose and 2" venting (see reference 20)	Assumes 11" DP cellulose and 2" venting
		Wall				
21		Framing	2x4, 16 o.c.	2x4, 16 o.c.	2x4, 16 o.c.	2x4, 16 o.c.
22	🟨	Insulation nominal R-value	R-6.75	R-19.8	R-12.46	R-19.8
		Assembly effective R-value	R-8.8	R-13.5	R-11.5	R-13.5
		Description	Non-continuous insulation, cavity only	Assumes 3" closed-cell SPF in cavity only	Assumes 3.5" DP cellulose in cavity only	Assumes approximately 5.5" DP cellulose in cavity only
		Windows				
23	🟦	Area	395 sf	395 sf	395 sf	395 sf
24	🟦	U-Factor	0.49	0.49	0.49	0.49
25		SHGC	0.40	0.40	0.40	0.40
		Doors				
26		Area	80.4 sf	80.4 sf	80.4 sf	80.4 sf
27		R-value	R-1.7	R-1.7	R-1.7	R-1.7
		Air leakage				
28	🟨🟦	ACH50	12	8.4	8.4	8.4
		Mechanical Systems				
		Heating				
29	🟨	System type	Boiler	Boiler	Boiler	Boiler
30	🟨	Fuel	Oil	Oil	Oil	Oil
31	🟨	Efficiency (AFUE)	83%	83%	83%	83%
32		**Cooling**				
33	🟨	Present (Y/N)	N	N	N	N
34		**Thermostat**				
35	🟦	Programmable (Y/N)	N	N	N	N

36	🟦	Heating set point	64.6	64.6	64.6	64.6
		Water heating				
37	🟨	Type	Direct	Direct	Direct	Direct
38	🟨	Fuel	Elect.	Elect.	Elect.	Elect.
39	🟨	Efficiency (EF)	0.69	0.69	0.69	0.69
40		Size	40 gal	40 gal	40 gal	40 gal
		Ventilation				
		Type	Exhaust only	Exhaust only	Exhaust only	Exhaust only
41	🟨	CFM	43	43	43	43
42		Hours/day	2.3	2.3	2.3	2.3
43		Watts	50	50	50	50
		Lighting & Appliances				
		Lighting				
	🟦	Percent incandescent	53% saturation (sockets filled)	53% saturation (sockets filled)	53% saturation (sockets filled)	53% saturation (sockets filled)
	🟦	Percent CFL	36% saturation	36% saturation	36% saturation	36% saturation
	🟦	Percent LED	11% saturation	11% saturation	11% saturation	11% saturation
		Appliances				
44	🟦	Refrigerator	693 kWh/yr	693 kWh/yr	693 kWh/yr	693 kWh/yr
45	🟦	Dishwasher	Standard (LER: 307)	Standard (LER: 307)	Standard (LER: 307)	Standard (LER: 307)
46	🟦	Clothes washer	Standard (IMEF: 1.21)	Standard (IMEF: 1.21)	Standard (IMEF: 1.21)	Standard (IMEF: 1.21)
47		Clothes dryer	Standard (CEF: 3.11)	Standard (CEF: 3.11)	Standard (CEF: 3.11)	Standard (CEF: 3.11)
		Extra fridge	No	No	No	No
		Freezer	No	No	No	No

Data Sources and References

🟨	Source = HERO data
🟦	Source = VT Department of Public Service 2017 Existing Homes Baseline Study https://publicservice.vermont.gov/sites/dps/files/documents/VT%20SF%20Existing%20Homes%20Overall%20Report%20-%20FINAL%20022719.pdf Note: The unpublished 12/21/2017 draft version of this report contains more detailed existing homes characteristics utilized to inform modeling of the existing home case.

Where input values are not based on either HERO data or the Baseline Study, professional judgment or other data source noted in the References was used to inform input values.

References

1 Average conditioned floor area

2 Most common # floors

3 Most common # bedrooms

4 Default

5 Most common type.
- Conditioned = intentionally heated / cooled to maintain set points
- From HERO, there were 9,818 total projects, of which 7,488, or 76%, had unheated basements (either above or below grade)

6 NOTE: Effective assembly R-values entered into OpenStudio. To obtain this value, most common assembly framing + average nominal insulation value was entered into REM/Rate to generate effective assembly efficiency.

7 *If present dependent on foundation type (model insulation either/or, but not both).
Most common insulation location at foundation.

8 Most common (e.g. 2x10, 16 o.c.)

9 Insulation modeled at foundation.

10 From HERO data set (all values are averages):
All installed cases (2,853 total), gives pre of 5.8 and post of 21.7
For installed:
- DP cellulose: (52 total) pre = 6.5, post = 35
- Closed-cell foam: (2,559 total) pre = 5.7 and post = 21.5
- All insulation types excluding closed-cell foam = (294 total) pre = 6.4, and post = 23.4

11 *If present dependent on foundation type (model insulation either/or, but not both).
Most common insulation location at foundation.

12 Most common (concrete etc.)
From 2017 Existing Homes Baseline Study:
- About one-quarter (26%) of the buildings were constructed before 1939, and over one-half (57%) were constructed between 1960 and 1999.
- Since over half of projects were constructed after 1960, authors assumed concrete / block walls and note that other field stone / rubble walls would require other special attention or unique/customized approaches. This assumes the most "common" or average situation, per the data at hand.

13 Average

14 Average
From HERO, there were 9,818 total projects, of which 7,488, or 76%, had unheated basements (either above or below grade)
from the HERO data set for above and below grade walls, all installed cases (4,614 total), gives pre of 3.5 and post of 18.7
- Polyiso = 997 total, pre = 3.4, post = 18.3
- Closed-cell spray foam = 3,335 total, pre = 3.5, post = 18.9
- EPS = 17 total, pre = 3.0, post = 18.0
- XPS = 211 total, pre = 3.6, post = 17.3

15 Carbon Smart (Equivalent-R) alternative would have required a partial thickness board product which was not practical.

16 Attic hatches are excluded.

17 Most common - vented, unvented, conditioned
From HERO data set, installed work:
- Attic Open Cavity: (3,556 total), pre = 15.1, post = 56
(Only loose fill and closed-cell spray = 3,352 total, pre =15.2, post = 56.7)
(loose fill cellulose only = 3,077 total, pre =15.4, post = 58.2)
(closed-cell spray only = 275 total, pre =13.4, post = 39.3)
- Closed cavity ceiling: (2,634 total), pre=9.9, post = 33.1
(Only DP cellulose and closed cell spray = 2,216 total, pre = 9.4, post = 32.8)
(DP cellulose only = 1,349 total, pre =9.3, post = 28.6)
(closed-cell spray only = 867 total, pre = 9.6, post = 39.4)
- Closed cavity ceiling: (2,634 total), pre =9.9, post = 33.1
Common practice: closed-cell spray only, pre = 9.6, post = 39.4 (assumes 6" of SPF)
Carbon smart: DP cellulose only, pre = 9.3, post = 28.6 (assumes 5.25" DP cellulose and 2" venting)
- Authors did not include attic open cavity as an option because it already is a Carbon Smart approach typically, and the closed cavity ceiling will illustrate greatest potential for improvement

18 From 2017 study: Majority of vaulted ceilings constructed with 2x8 or larger members.

19 Average R-value

20 6" of closed-cell spray foam assumes two 3" installation "lifts" as is common practice. Venting is included in both Carbon Smart scenarios for DP cellulose as is required by code.

21 Most common (e.g., 2x4, 2x6), only cavity insulation was assumed, no continuous added

22 From HERO data: 42,451 total projects, of which 18,029 were installed (average existing R -8, improved R -31)
Installed wood framed walls = 2,690 total, average existing R -7, improved R -22
- Continuous - installed wood framed walls = 664 total, existing R -7.64, improved R - 24.1
- Non-continuous - installed wood framed walls = 2,026 total, existing R-6.75, improved R-21.57 (all materials)
- Densepack = 964, pre = 6.49, post = 19.35
- Closed-cell spray foam = 812, pre =7.07, post =24.03
- Polyiso = 150, pre = 6.7, post = 23.2

23 13% average glazing percentage of exterior wall area (27% to the south) from baseline study (see 2017 version)

24 Most common type: Double pane clear. REM/Rate default U-factor for window type.

25 Default value

26 Assumes four 3'x6'-8" doors

27 REM/Rate default R for steel-urethane foam door

28 See calculations and assumptions noted in report text under "Modeling Assumptions"

	12 ACH50 average from HERO data for homes 2,000-2,999 sf. 8.4 ACH50 assumes 30% reduction from all measures. Baseline study notes 9.5 ACH50 as the overall unweighted air leakage rate.
29	Most common
30	Most common
31	Average
32	Not included; most homes in the data set did not include cooling
33	Most common, present or no
34	Can use from study if known, otherwise use standard settings
35	From 2017 baseline study. Majority manual (~69%)
36	From 2017 baseline study
37	Most common
38	Most common
39	Average
40	Default
41	Average
42	EVT TRM Portfolio 2020-01 (Measure: RS-HVC-ESRVF a)
43	Vermont Residential Building Energy Standards maximum allowable wattage
44	Per baseline study: 22% ENERGY STAR; EVT TRM (Measure: RS-RFG-EERFG n)
45	Per baseline study: 45% ENERGY STAR; REM/Rate default settings for federal minimum
46	Per baseline study: 45% ENERGY STAR; REM/Rate default settings for Standard 2008-2017
47	EVT TRM Portfolio 2019-01 (Measure: IV-A-2 d)

Appendix B: Operational Emissions Savings of Compared Scenarios Over Time

The below figures illustrate the operational savings of each of the modeled scenarios over a 10-year period as a point of comparison between measures. Note that the 'Carbon Smart (Equivalent-R)' scenario does not appear in the charts that follow because the operational savings are the same as for 'Common Practice'.

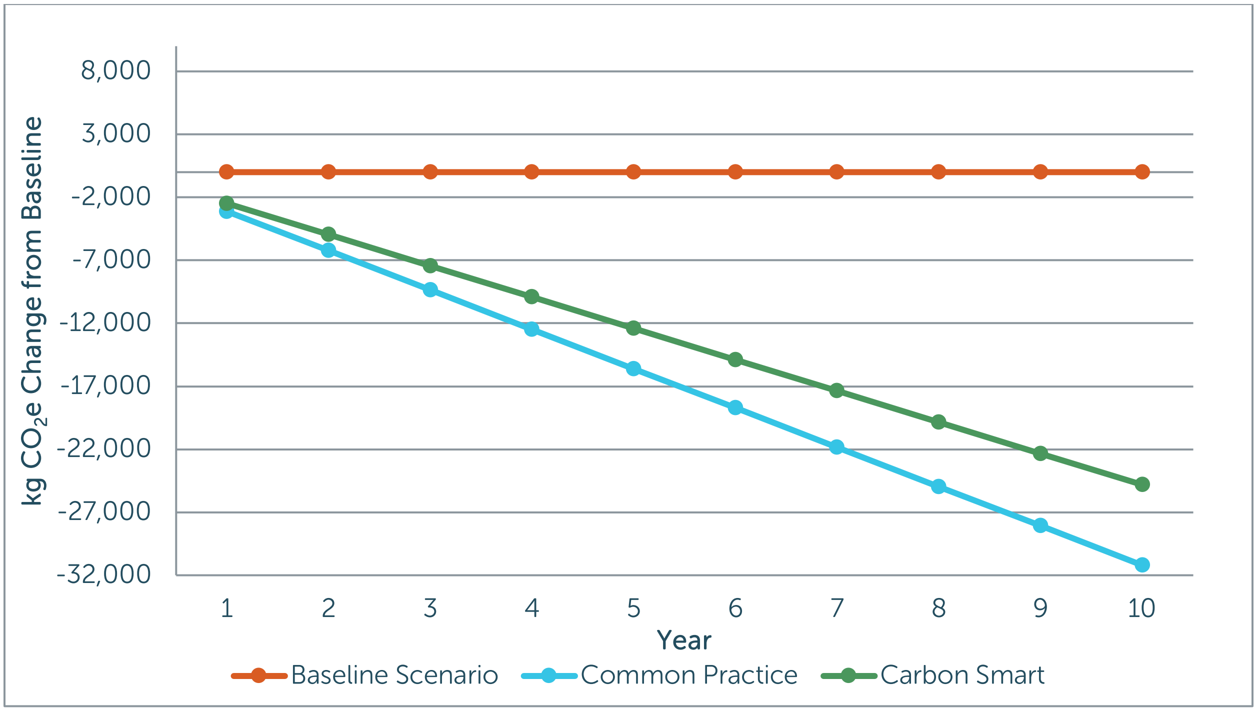

Figure B-1: Operational kg CO_2e savings over time - all measures

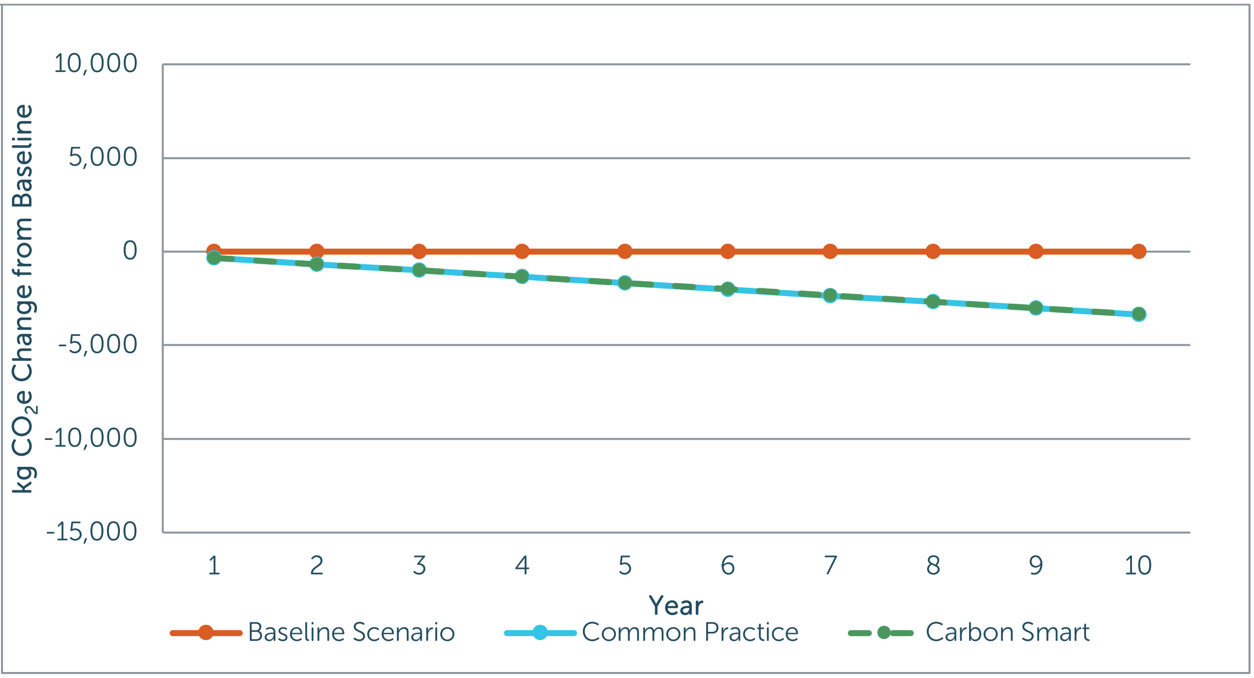

Figure B-2: Operational kg CO_2e savings over time - foundation insulation

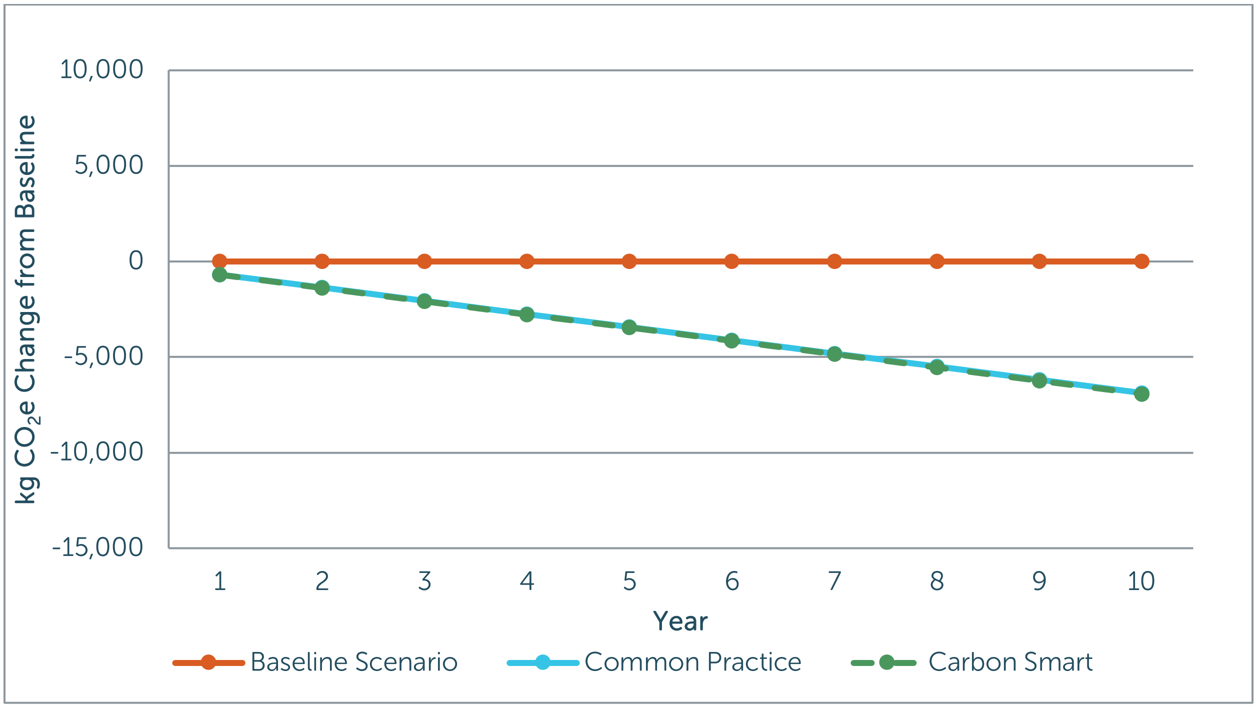

Figure B-3: Operational kg CO_2e savings over time - band joist insulation + air sealing

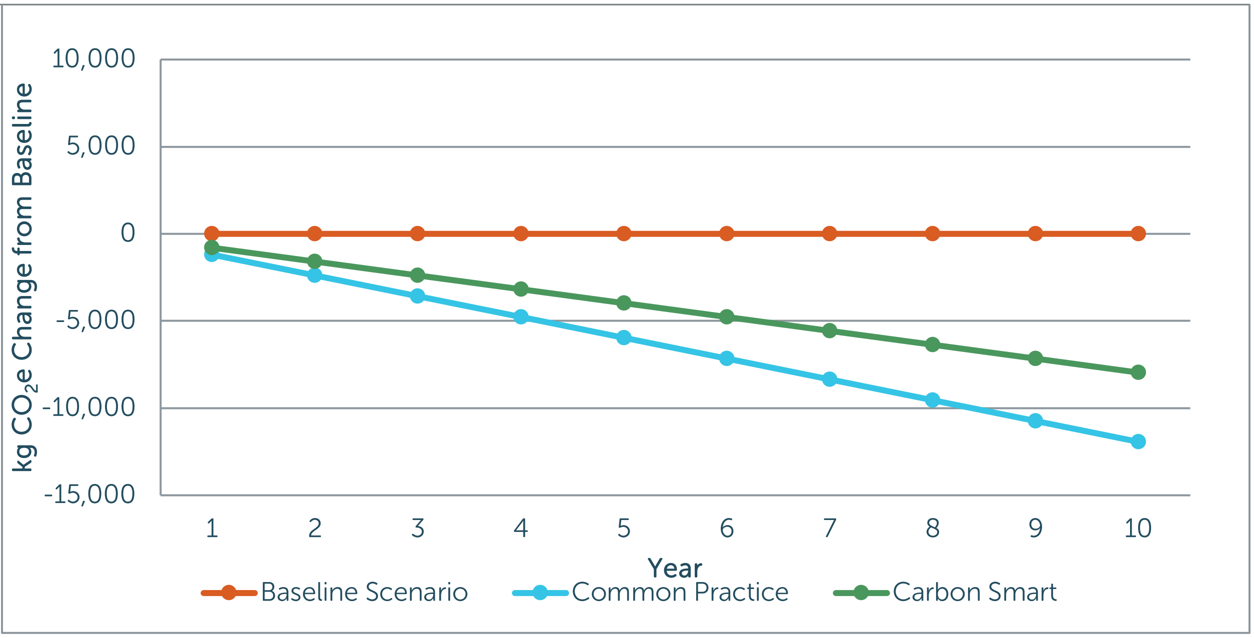

Figure B-4: Operational kg CO_2e savings over time - wall insulation + air sealing

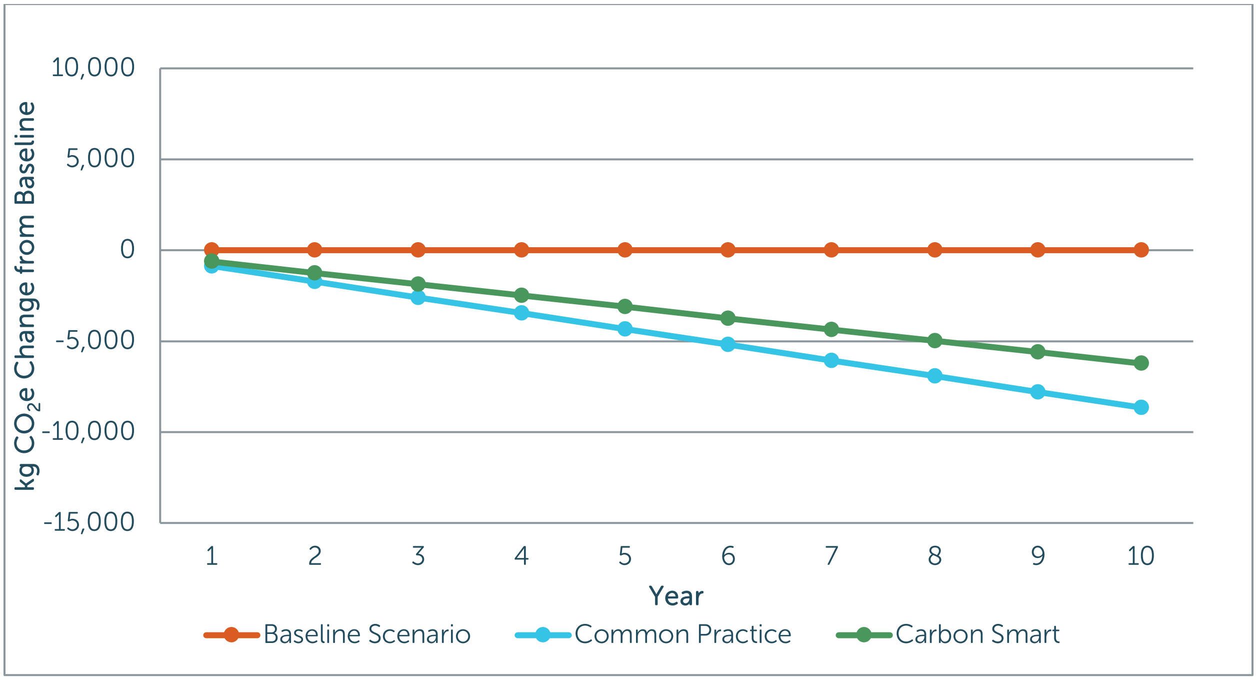

Figure B-4: Operational kg CO_2e savings over time - ceiling insulation + air sealing

Appendix C: Carbon Emissions (Embodied and Operational) Over Time by Measure

Figures C-1 through C-4 below illustrate the carbon emissions (embodied and operational) over time for each weatherization practice. Overlap in Carbon Smart approaches is designated with a dashed line.

The carbon emissions (embodied and operational) of the three weatherization scenarios at the foundation walls (C-1) is negligible. The Common Practice scenario (3" of closed-cell HFO spray foam) has a slightly higher R-value than that of the Carbon Smart scenario (3" of polyisocyanurate foam); however, the embodied carbon emissions of the HFO foam is greater than that of the polyisocyanurate foam, so they nearly offset each other The authors note that the Carbon Smart (Equivalent-R) alternative would require a partial thickness of a rigid foam board, which is not logical. The R-values are nearly equivalent between the two scenarios.

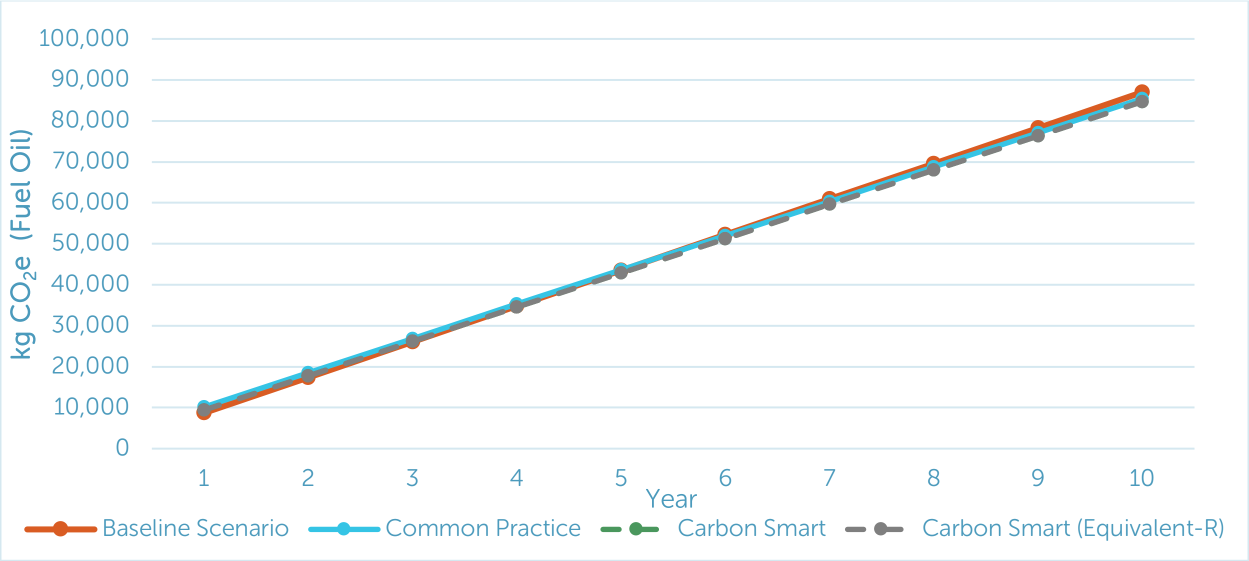

Figure C-1: kg CO_2e emissions (embodied and operational) over time -foundation insulation

As Figure C-2 illustrates, the carbon emissions (operational and embodied) of the three weatherization scenarios at the band joists is also negligible. The R-values of the Common Practice scenario (3" of closed-cell HFO spray foam) were assumed as equal with the two Carbon Smart scenarios (5.5" of DP cellulose insulation). The operational carbon emissions are therefore the same, and although the embodied carbon emissions of the HFO foam is significantly higher (146 kg CO_2e) than the DP cellulose and air-sealing caulking (–122 kg

CO_2e), over time the operational emissions overwhelm the embodied emissions, yielding comparable outcomes for the two scenarios.

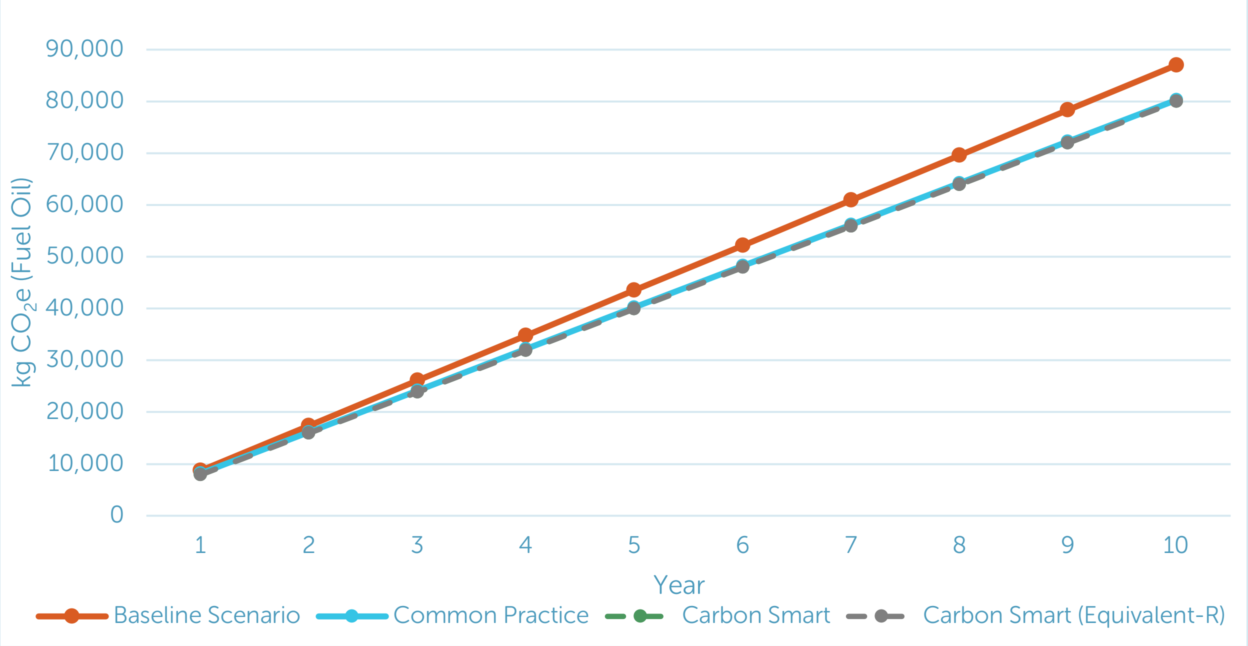

Figure C-2: kg CO_2e emissions (embodied and operational) over time - band joist insulation + air sealing

For wall weatherization measures (Figure C-3), again both of the Carbon Smart approaches have lower emissions (operational and embodied) than the Common Practice measure beginning in the first year. The emissions (embodied and operational) of the Carbon Smart measure meet those of the Common Practice measure in year five, while the Carbon Smart (Equivalent-R) measure continues to have the lowest emissions. As the Carbon Smart (Equivalent-R) measure has the same operational emissions as the Common Practice, the embodied carbon emissions account for the difference between these two scenarios.

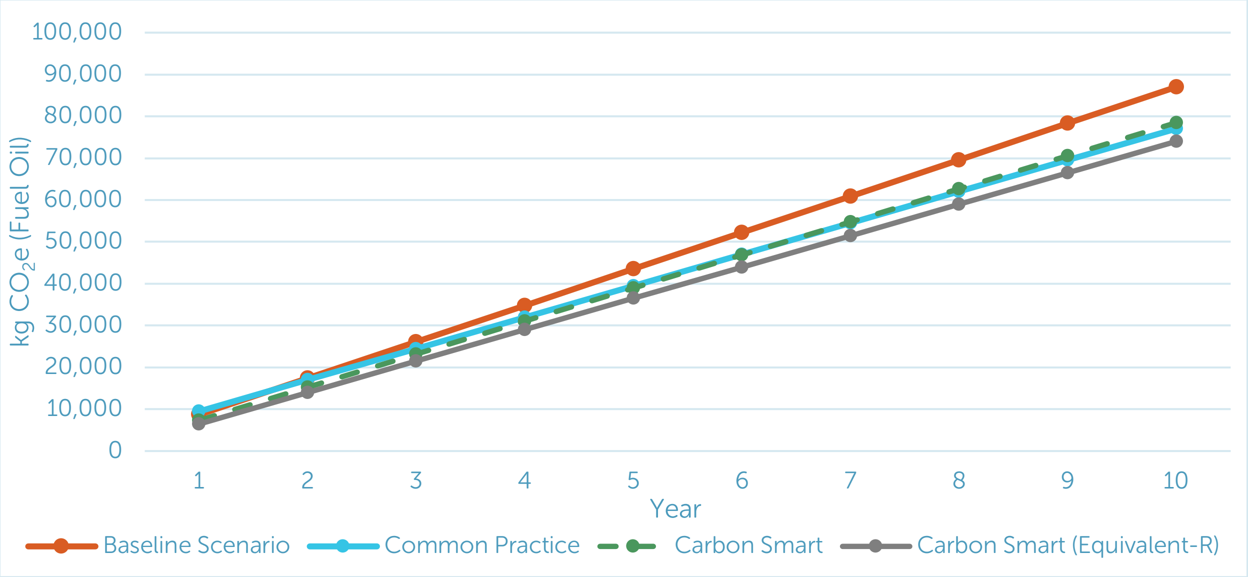

Figure C-3: kg CO_2e (embodied and operational) over time - wall insulation + air sealing

For ceiling measures (Figure C-4), both of the Carbon Smart approaches also have lower emissions (embodied and operational) than the Common Practice measure beginning in the first year and continuing for 10 years. At that point, the Carbon Smart (Equivalent-R) scenario has an increasingly favorable carbon impact, while the Carbon Smart approach is equalized with the Common Practice approach.

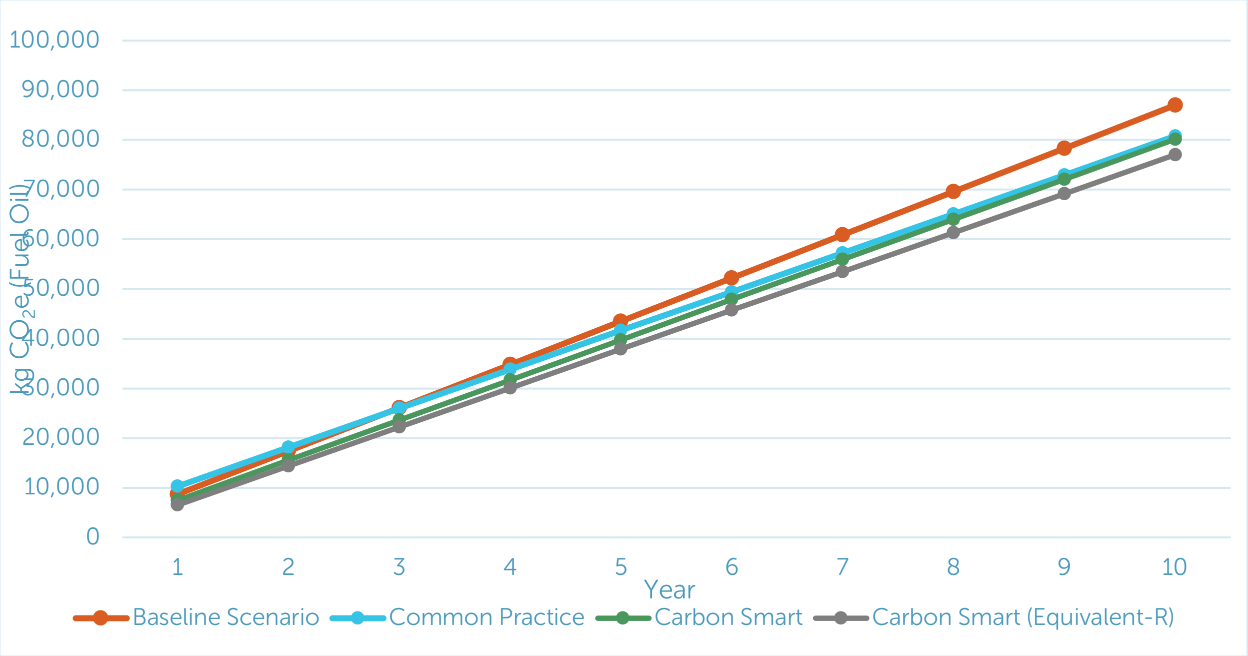

Figure C-4: kg CO_2e emissions (embodied and operational) over time - ceiling insulation + air sealing

Table C-1 shows the CO_2e emissions values over time for all measures.

Table C-1: kg CO_2e emissions (embodied emissions + annual operational emissions) over time - all measures

Year	1	2	3	4	5	6	7	8	9	10
Baseline Scenario	9,000	17,000	26,000	35,000	44,000	52,000	61,000	70,000	78,000	87,000
Common Practice										
Basement insulation with no air leakage reduction	10,000	19,000	27,000	35,000	44,000	52,000	60,000	69,000	77,000	85,000
Band joist insulation with associated 17% air leakage reduction	8,000	16,000	24,000	32,000	40,000	48,000	56,000	64,000	72,000	80,000
Wall insulation with associated 8.3% air leakage reduction	9,000	17,000	24,000	32,000	40,000	47,000	55,000	62,000	70,000	77,000
Ceiling insulation with associated 4.7% air leakage reduction	10,000	18,000	26,000	34,000	42,000	49,000	57,000	65,000	73,000	81,000
Whole house upgrade with associated 30% air leakage reduction	12,000	18,000	23,000	29,000	34,000	40,000	45,000	51,000	57,000	62,000

Year	1	2	3	4	5	6	7	8	9	10
Carbon Smart										
Basement insulation with no air leakage reduction	9,000	18,000	26,000	35,000	43,000	51,000	60,000	68,000	76,000	85,000
Band joist insulation with associated 17% air leakage reduction	8,000	16,000	24,000	32,000	40,000	48,000	56,000	64,000	72,000	80,000
Wall insulation with associated 8.3% air leakage reduction	7,000	15,000	23,000	31,000	39,000	47,000	55,000	63,000	71,000	78,000
Ceiling insulation with associated 4.7% air leakage reduction	7,000	16,000	24,000	32,000	40,000	48,000	56,000	64,000	72,000	80,000
Whole house upgrade with associated 30% air leakage reduction	6,000	12,000	18,000	25,000	31,000	37,000	43,000	49,000	56,000	62,000

Year	1	2	3	4	5	6	7	8	9	10
Carbon Smart (Equivalent-R)										
Basement insulation with no air leakage reduction	9,000	18,000	26,000	35,000	43,000	51,000	60,000	68,000	76,000	85,000
Band joist insulation with associated 17% air leakage reduction	8,000	16,000	24,000	32,000	40,000	48,000	56,000	64,000	72,000	80,000
Wall insulation with associated 8.3% air leakage reduction	6,000	14,000	21,000	29,000	36,000	44,000	51,000	59,000	67,000	74,000
Ceiling insulation with associated 4.7% air leakage reduction	7,000	14,000	22,000	30,000	38,000	46,000	54,000	61,000	69,000	77,000
Whole house upgrade with associated 30% air leakage reduction	4,000	10,000	15,000	21,000	26,000	32,000	38,000	43,000	49,000	54,000