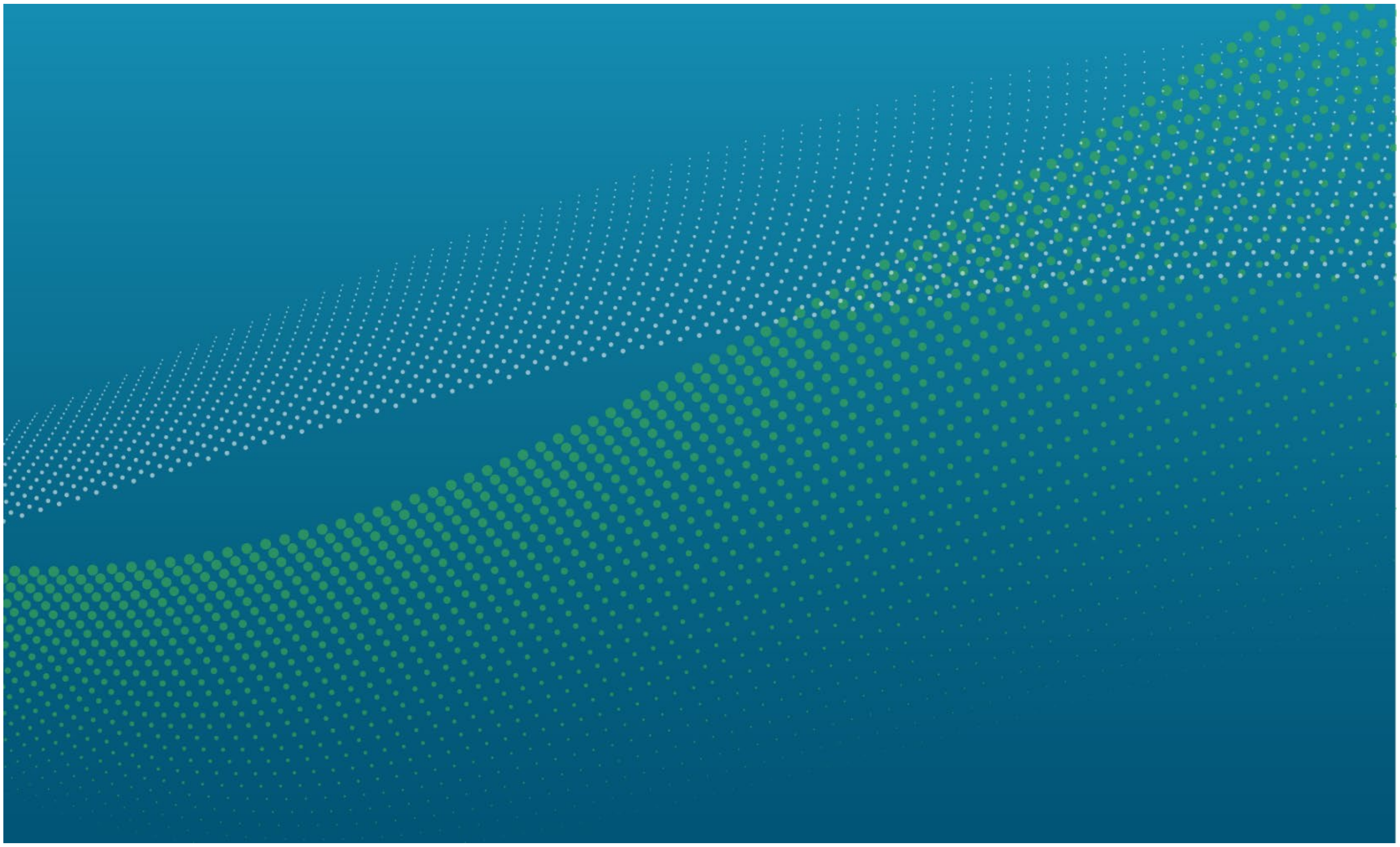

Embodied Carbon in Vermont Residential Retrofits

EFFICIENCY VERMONT R&D PROJECT: GREENHOUSE GAS REDUCTION

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Introduction

Customers who want to make their residences more energy efficient typically work with their contractors to choose home insulation materials. Their collective decisions involve cost effectiveness, durability of the materials, their regional availability, and how appropriate they are—from a building science perspective—for the project. Global environmental impacts have now also entered decision making, although there is some market confusion about what factors should be considered. This Efficiency Vermont Research and Development Program project sought to streamline customers' and contractors' decision making of global environmental impacts by deriving a single point of comparison for a wide variety of materials. The project has related that point of comparison, *embodied carbon,* to a growing body of literature on global warming potential. *Embodied carbon* for the purposes of this study counts all greenhouse gas-producing factors in the extraction, manufacturing, and installation of each material.

Efficiency Vermont and its partners for this project, New Frameworks and Vermont Integrated Architecture, have now filled a gap in the data on the embodied-carbon contribution of weatherization materials in Vermont's retrofit projects. This study analyzed completed Home Performance with ENERGY STAR® (HPwES) projects, the program standard for weatherization retrofits supported by Efficiency Vermont funds, from 2012 through 2016. The data from those projects allowed the study team to quantify the embodied carbon associated with residential retrofit projects. The team subsequently analyzed how that impact would differ if materials with lower embodied carbon emissions had been used. This information can assist customers, contractors, and design professionals in understanding the extent to which insulation materials factor into the total carbon emission contribution of a given retrofit project.

The focus on evaluating the embodied carbon emissions of building materials holds relevance in the weatherization sector given that:

1) Some of the most emission-intensive materials are commonly used for thermal enclosure improvements.

2) The goals and intentions of many weatherization projects are to reduce the home's carbon footprint by reducing energy consumption; therefore, it is critical to understand the impact of the materials selected in pursuit of these goals for their intentions to be realized.

The time scale in which emissions are released is highly relevant in their impact; whereas operational carbon emission reductions due to energy savings are realized incrementally over time with the passing of annual heating and cooling seasons, embodied carbon emission reductions from materials are realized immediately, as the emissions are released during the production of the materials at the very beginning of the project's lifespan. Given the very short period of time within which we must dramatically reduce the building sector's carbon emission profile, as identified by the Intergovernmental Panel on Climate Change[1], this time scale of

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[1] The IPCC is a body of the United Nations focused on assessing the science of climate change; https://www.ipcc.ch/

emission release bears great relevance, as operational energy reduction alone will be insufficient to meet these goals.

Research Tasks

1) Determine and illustrate the density of HPwES projects in Vermont by geographic location.

2) Determine the types of insulation materials used in specific residential building assemblies (walls, attics, band joist, foundation walls) and if/how these choices have changed across the five-year period.

3) Characterize the embodied carbon emissions by application type to understand:
    a) which types contribute most to CO_2e (carbon dioxide equivalent) emissions

    b) which applications are the most carbon intensive[2]

4) Illustrate the evolution of HPwES installations and the associated overall upfront embodied carbon emissions over time (by material and application).

Methods

Efficiency Vermont derived the HPwES 2012 – 2016 dataset from contractor inputs in the energy efficiency utility's HERO tool.[3] The study team sorted the data to identify only completed projects with installed measures, excluding entries listed as "recommendations."

The team then reviewed the data set for outliers and errors associated with user inputs and removed them. The team set parameters for reasonable inputs on Vermont's housing stock, and deleted data falling outside those boundaries because they might have been either invalid or the result of user error.

For each application, the team calculated a ratio of treated area to total home area, except for attic hatches, where there is less relationship between area of hatch and area of home. The team established an upper boundary to reject clear outliers; these accounted for no more than 5 percent of the total data set for each application. The team then calculated the resulting average and the standard deviation from the average, establishing the standard deviation as a new upper boundary, and thus further rejecting outliers, representing between 13 and 21 percent of the remaining dataset after the initial outliers were removed. One single project

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[2] Carbon intensity is the emission rate of a greenhouse gas (GHG), relative to the energy intensity of a specific use (an activity or industrial production process, for example).

[3] Contractor project-reporting tool that enables Efficiency Vermont visibility into project details. 2012-2016 represents a five-year span with consistent data fields in the tool.

contained no information about square footage and was thus removed from the data set. The team did not establish a lower boundary, recognizing that small projects frequently improve only a small percentage of the total area in a given home.

This study defines the following terms:

I. *Materials:* insulation types used at any of the various applications, defined by the HPwES program reporting structure:
    - Cellulose, dense pack
    - Cellulose, loose fill
    - Expanded polystyrene- rigid board
    - Extruded polystyrene- rigid board
    - Fiberglass batts
    - Fiberglass- loose fill
    - Poly-isocyanurate- rigid board
    - Spray foam- closed cell
    - Spray foam- open cell

II. *Applications*: The physical space in a building in which a "practice" has been applied, as defined by the HPwES program reporting structure:
    - Attic hatch
    - Attic, open cavity
    - Basement, above grade
    - Basement, below grade
    - Basement rim joist
    - Closed-cavity ceiling
    - Floor
    - Wood-framed wall

III. *Practices* and *measures*: installed insulation materials at defined thicknesses (in units of inches added) for each physical space, with an indication of the net square feet treated).

IV. *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.[4] R-values for materials are expressed as the R-value per inch of material.

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

VI. *Embodied carbon emissions:* total greenhouse gas emissions that result from the extraction, processing, manufacturing, transportation, and installation of building

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[4] 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 webpage on insulation: https://www.energy.gov/energysaver/weatherize/insulation.

materials. The focus for this study is on upfront embodied carbon emissions covering material extraction through installation, whereas a more comprehensive definition of embodied carbon may include emissions released throughout the entire lifespan of the material. See Table 1 for more detail on life cycle analysis (LCA) product stages.

The study team approached each research task as follows, using the Efficiency Vermont HPwES program dataset as its primary information source:

1. *Density of installed HPwES measures, by geographic location.*
   The team sorted and examined the dataset, removing null entries. For this task, the team did not differentiate projects by material, application, or the year of project completion. Counties were chosen as the geographic study unit.

2. *Types of insulation used in specific residential building assemblies and if/how these choices have changed over time.*
   The team sorted projects by application and material type with quantities calculated for each. Relative carbon impact was not considered in this analysis task. Results were then sorted by year to illustrate trends of applied practices over time.

3. *Embodied carbon emissions by application type*
   The team sorted projects by application and material used. It also applied the global warming potential (GWP) emissions factor, expressed as kilograms of carbon dioxide equivalence (kg CO_2e),[5] for each material based on averages derived from Environmental Product Declaration (EPD) data.[6] The study team used the Product Stage (A1-A3) 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 installation. Carbon storage value, discussed later, was also accounted for in cellulose installations.

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[5] Carbon dioxide equivalence units offer a shorthand way to address the impacts from all greenhouse gases, beyond only the primary pollutant, carbon dioxide. The other significant heat-trapping gases are methane, nitrous oxide, and refrigerant gases.

[6] The International EPD system is a global program for environmental product declarations. For general information about the program, to search for products with EPDs, and to obtain information on how to create an EPD, see *https://www.environdec.com*.

Table 1. Life cycle stages, using terms from the European standard EWN 15978[7]

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

The team then calculated the quantity of material/type of insulation used in each project application, by the number of inches of each material for each type of insulation installed. From this information, the team calculated the total embodied carbon emissions by project application by summing the value of the embodied carbon emissions of each material used, and with consideration for carbon stored from biogenic materials, where applicable. See below for additional discussion regarding carbon storage calculations for biogenic materials.

Table 2. GWP of insulation material and R-value summary (partial list)

Material	**Form or variant**	**R-/"**	**GWP average $kgCO_2e$ *[A1+A2+A3]* per m^2 RSI-1**	**GWP average* $kgCO_2e$ *[w / A5+B1]* per m^2 RSI-1**	**GWP components**
Cellulose	Blown / loosefill, 1.29 pcf	3.38	0.49	-0.83	A5, Carbon Storage
Cellulose	Densepack, 3.55 pcf	3.56	1.27	-2.16	A5, Carbon Storage
Expanded polystyrene (EPS)	Board, unfaced Type IX-25psi, graph.	4.70	3.47	3.49	A5
Fiberglass	Batt, unfaced, recycled content	3.64	0.67	0.68	A5
Fiberglass	Blown / loosefill	2.68	1.29	1.30	A5
Polyisocyanurate	Board, foil-faced	6.53	2.32	2.32	Not given
Spray polyurethane foam (SPF)	Spray, closed-cell hyrdofluorocarbons (HFC)	6.60	3.31	14.86	A5, B1
SPF	Spray, closed cell hydrofluoroolefins (HFO)	6.60	3.47	4.00	A5, B1
SPF	Spray, open cell	4.05	1.42	1.59	A5, B1
Extruded polystyrene (XPS)	Board, 25psi	5.00	20.17	46.51	A5, B1

Source: Just, Brian, 2020. *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. Winooski, VT. * Averages used in this study are based on 100-year GWP value and appear in highlighted column.

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[7] The European Committee for Standardization's EN 15978 addresses sustainability of construction work and assesses environmental performance of buildings. See *Introduction to LCA of Buildings,* Danish Transport and Construction Agency, 2016. https://www.trafikstyrelsen.dk/en/-/media/TBST-EN/Byggeri/Introduction-to-LCA-of-Buildings.pdf.

No differentiation was given for the year of completion. Because some applications had far more installations than others, the team considered the average CO_2e impact per application to illustrate which are the most carbon intensive. For the purposes of this study, the GWP values of HFO-type closed-cell spray polyurethane foam (SPF) insulation were used to reflect the growing market share of this material and expected near-term phase-out of the more carbon intensive HFC-based products. In practice, although the data set does not specify the nature of the SPF product used, the project team expects a significant portion of the SPF applications in this study used HFC-type foam which would increase emissions for those measures by 370%, highlighting the importance of careful SPF product selection; see Discussion for more information.

Carbon storage values were assigned to bio-based materials as an expression of the carbon dioxide removed from the atmosphere and photosynthesized into biogenic carbon present in the material. To quantify this value, the percentage of biologic content in the material was determined from the product EPD and applied 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 gleaned from EPDs 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. The resulting value is the kg CO_{2e} stored in the material, expressed as a negative value (emissions reduced from the atmosphere). 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 carbon emission at the end of the building’s life cycle. The decision whether to value carbon 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 predominately from recycled paper and cardboard diverted from the waste stream, and therefore the project team holds confidence in the valuation of carbon storage for this material.

4. *The evolution of installations and the associated overall embodied carbon emissions over time (by application and material).*

After completing the first three tasks, the team sorted the results by year, to illustrate any relevant trends over time. To complete the analysis by project application, the team did not differentiate results by material type, and vice versa for the analysis by material type. In each case, the team included the number of installations per year, because an increase or decrease in the number of measures in any given year could help explain an overall increase or decrease in carbon impact.

Results and Analysis

Research Task 1: Illustrate the density of installed HPwES measures in Vermont by geographic location.

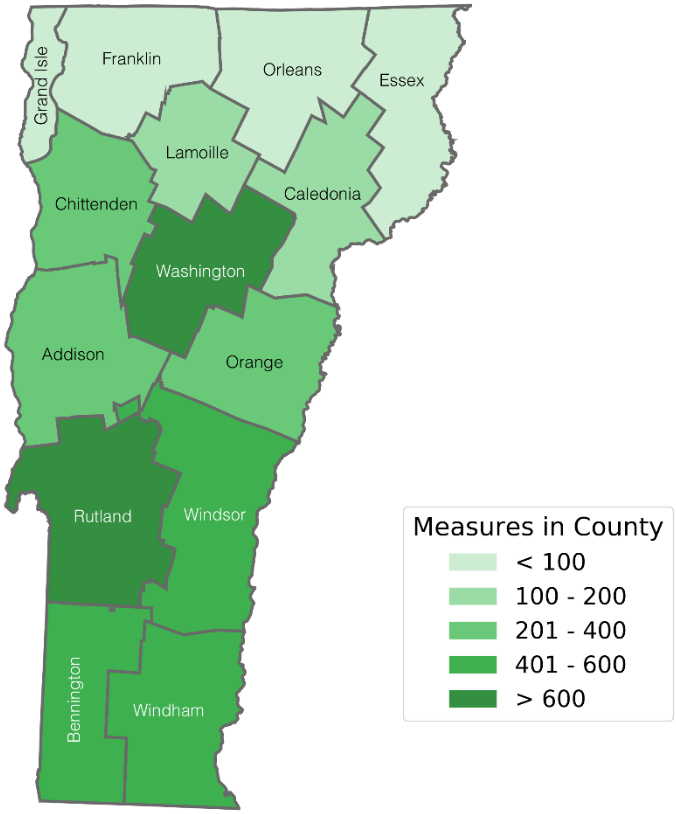

Figure 1: Relative density of completed HPwES measures by county

Figure 1 shows the concentration, by total count, of HPwES weatherization measures installed in Vermont between 2012 and 2016. Washington and Rutland counties have the highest counts.

Research Task 2: Determine the types of insulation materials used in specific residential building assemblies (walls, attics, band joist, foundation walls) and if/how the use of these materials has changed over time.

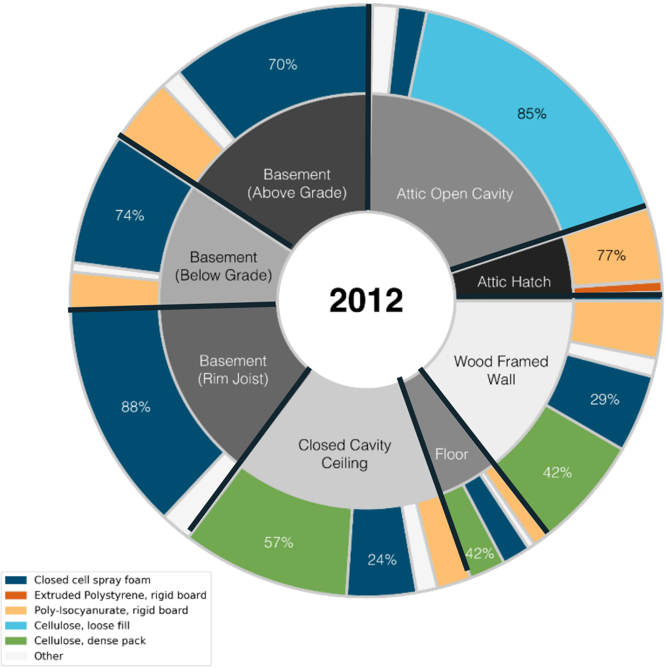

Figure 2. Types of insulation used to retrofit residential building assemblies- 2012

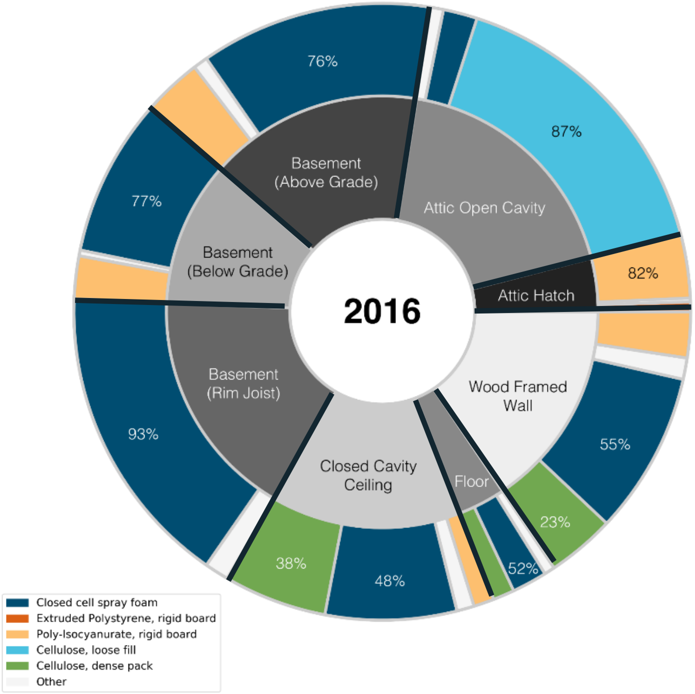

Figure 3: Types of insulation used to retrofit residential building assemblies- 2016

Figures 2 and 3 break out the type of insulation used in building assemblies at the beginning of the analysis period (2012) and at the end (2016). The proportionality of building assemblies receiving insulation remained fairly constant throughout the study period and the insulation type used remained largely unchanged for many assemblies. Closed cavity ceilings and wood framed walls, however, showed a proportional increase in the use of closed cell spray foam. By contrast, the use of dense pack cellulose in those assemblies decreased. See additional analysis in the *Discussion* section and 2013-2015 figures in the Appendix.

Table 3: Material use change in closed cavity ceilings and wood framed walls

Closed Cavity Ceiling (2012)	Closed Cell SPF	24%	Dense Pack Cellulose	57%
Closed Cavity Ceiling (2016)	Closed Cell SPF	48%	Dense Pack Cellulose	38%
Wood Framed Walls (2012)	Closed Cell SPF	29%	Dense Pack Cellulose	42%
Wood Framed Walls (2016)	Closed Cell SPF	55%	Dense Pack Cellulose	23%

Research Task 3: Characterize the embodied carbon emissions by application type to understand:

a) *which applications contribute most to CO_2e emissions*
b) *which applications are the most carbon intensive*

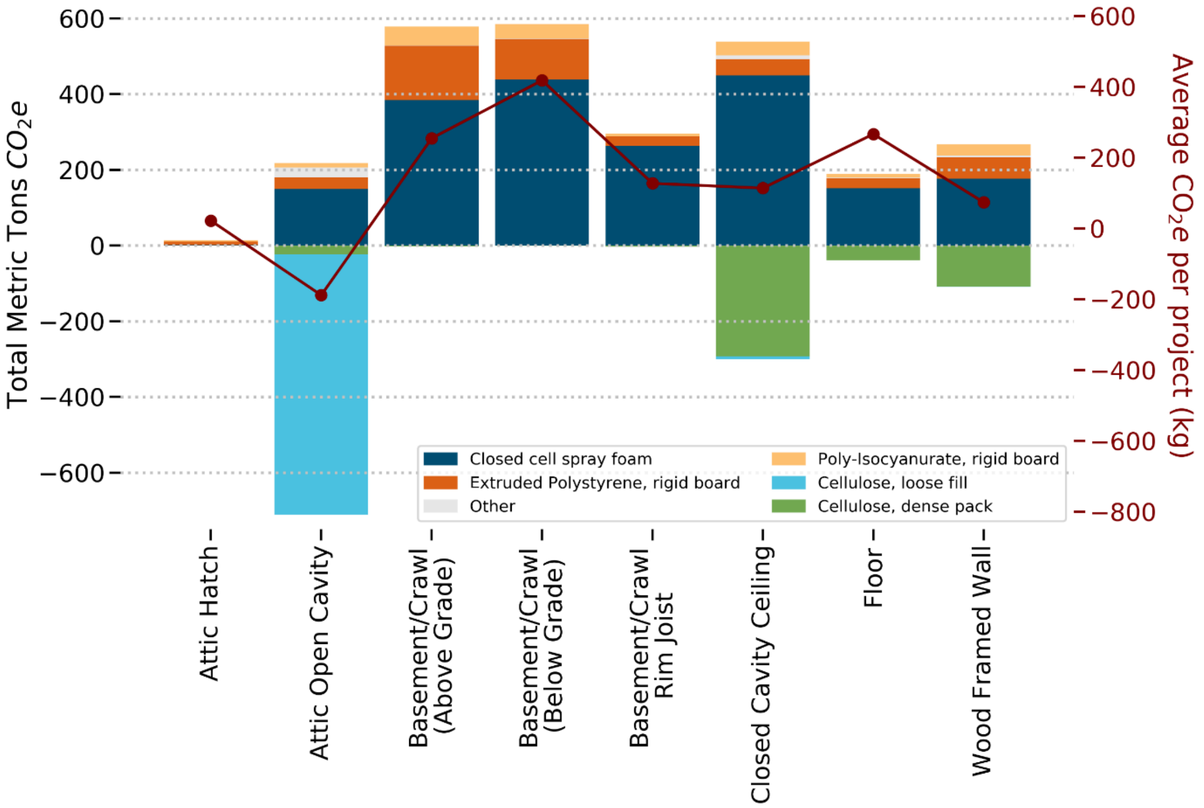

Figure 4: Embodied Carbon emissions by application type

Figure 4 indicates that open attics benefit from widely adopted use of cellulose which has high carbon storage value. Basements, floors, and crawl space applications have high embodied carbon emissions because they often rely on closed-cell spray foam to address variations in surface contours and moisture levels in those locations.

Research Task 4: Illustrate the evolution of HPwES installations and the associated overall upfront embodied carbon emissions over time (by material and application).

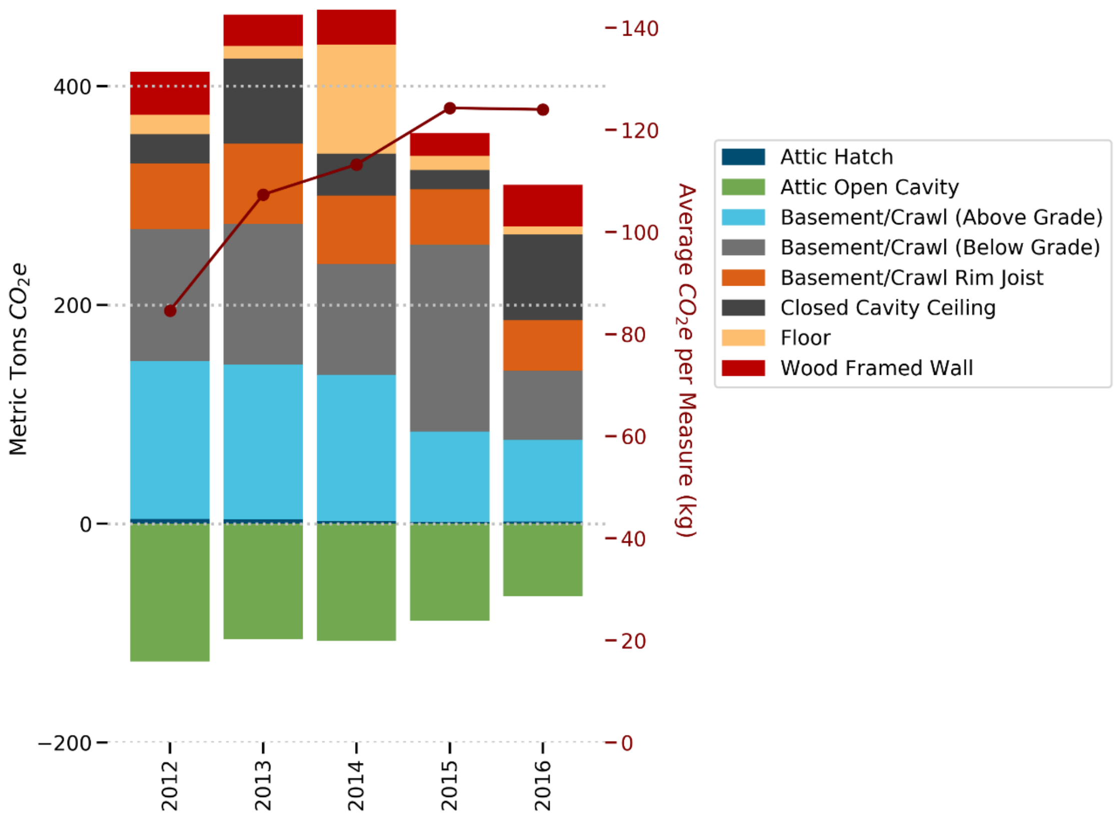

Figure 5: The evolution of measure installations and the associated overall embodied carbon emissions over time (by application).

Figure 5 illustrates overall carbon emissions impact over time, organized by application, compared to the average CO_2e per HPwES per measure installed annually. The annual number of measures per year is proportional to the size of each bar and is relevant because an increase or decrease in the number of measures in any given year can help explain an overall increase or decrease in total carbon impact. The trendline shows an overall increase in average CO_2e per measure during the study period signifying increased use of more carbon-intensive practices.

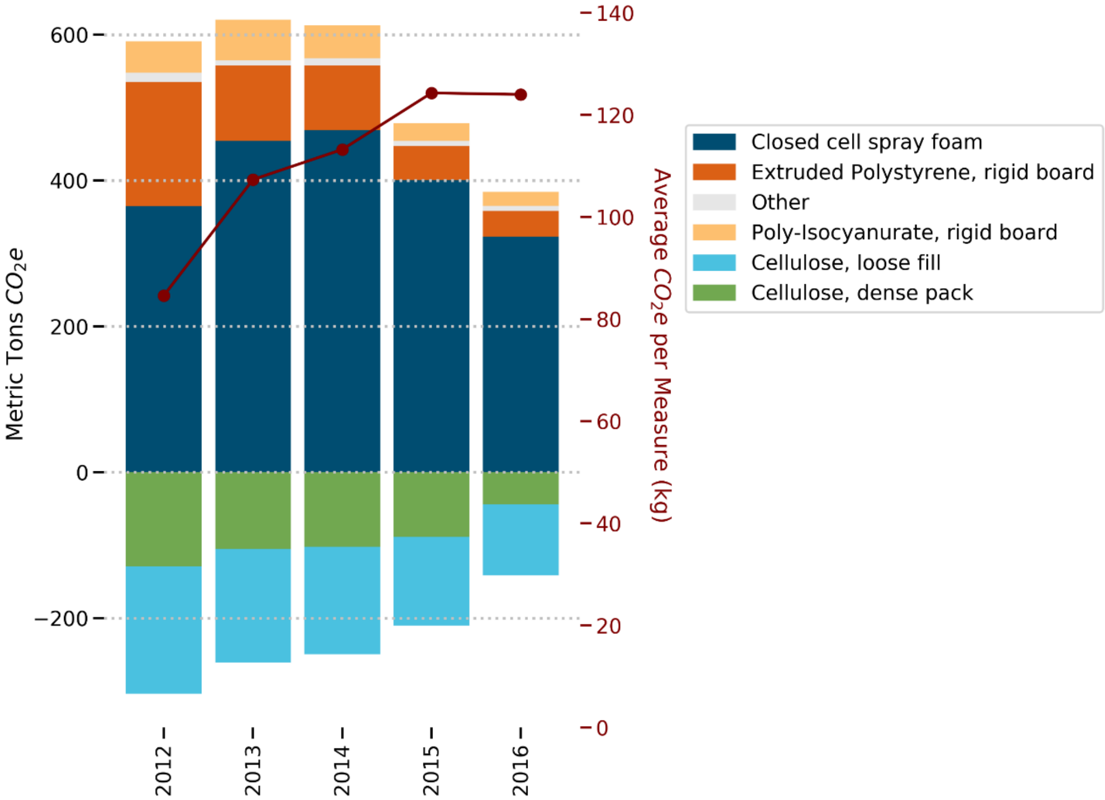

Figure 6: The evolution of installations and the associated overall embodied carbon emissions over time, by material.

Figure 6 presents information similar to that shown in Figure 5, but is broken out across the analysis period by material type, instead of location, to show the overall evolving picture of carbon emissions associated with material selections of HPwES weatherization work. The CO_2e totals are higher in Figure 6 compared to Figure 5 given that an application could comprise multiple insulation types that combine negative embodied CO_2e (ex. cellulose) *and* positive embodied CO_2e (ex. closed cell spray foam or XPS) resulting in a net reduction in overall embodied carbon for a particular location.

Discussion

As can be seen by results of this study, there are clear correlations between the embodied carbon emissions of a given practice and the materials selected to be installed in that application. Bracketing the highest and lowest impact materials that are directly interchangeable in many cases are closed-cell spray foam and cellulose insulation. Even when normalized for comparable installed R-value, the embodied carbon impacts of the closed-cell spray foam applications are significant, whereas the carbon storage value of the cellulose is realized immediately by virtue of the diversion of recycled biogenic material from the waste stream (see Methods VI.3. for more information). Even when this storage value is not considered, the embodied carbon emissions of cellulose are a fraction of those from closed-cell spray foam (1.27 vs 4.00 (HFO) or 14.86 (HFC) kg CO$_{2e}$ per M^2-R$_{SI-1}$, respectively; see Table 2). With the exception of XPS board insulation, the other materials fall in a range of emission impact in between these two materials (see Table 2).

Starting in 2021, a planned phase-down of hydrofluorocarbons (HFCs) in foam insulation materials sold in Vermont is going into effect as a result of Act 65.[8] Prior to this 2019 legislation closed cell spray foam was already seeing a shift away from hydrofluorocarbon (HFC) blowing agents toward hydrofluoroolefin (HFO) blowing agents. The HFC rules will further reduce the overall global warming potential of foam products like closed cell spray foam and extruded polystyrene (XPS). Discrepancies in embodied carbon of insulation materials- while not as significant - will remain when accounting for carbon storage benefits of plant-based insulation products like cellulose.

Material Selection Impact: Closed Cavity Ceilings

Between 2012 and 2016 there is a noticeable increase in the use of closed cell spray foam to insulate closed cavity ceilings. In 2012, 57% of closed cavity ceilings had dense pack cellulose insulation while 24% were insulated with closed cell spray foam. In 2016, closed cell spray foam doubled to 48% while cellulose use dropped to 38%. Primarily as a result of this shift in material selection, the average embodied carbon impact of insulating closed cavity ceilings increased by 231 kg CO$_2$e per project, the equivalent of 573 miles driven in an average passenger vehicle[9].

Material Selection Impact: Open Cavity Attics

Figure 4 identifies the single largest source of embodied carbon storage by application: open cavity attics. This can be correlated to the use of loose-fill cellulose insulation as the dominant insulation choice throughout the analysis period (85-87%). Whereas other applications in the building trend towards more embodied carbon-intensive materials or a changing mix of materials trending away from cellulose, this application highlights a consistent bank of stored embodied carbon throughout HPwES projects across the timeframe of the analysis.

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[8] The proposed rule and timeline for HFC drawdown can be found on the Vermont Department of Environmental Conservation website: https://dec.vermont.gov/sites/dec/files/aqc/laws-regs/documents/Vermont_HFC_Proposed%20Rule_DRAFT_19May2020_CLEAN.pdf

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

Material Selection Impact: Basement Walls and Rim Joists

Throughout the analysis period, the use of closed-cell spray polyurethane foam (SPF) is the dominant material choice for above-grade basement walls (68-79%), below-grade (72-78%), and rim joist (87-93%) applications between 2012 and 2016. In the field, these three applications are frequently executed as a single measure; therefore, material selections for one application are generally applied across all three applications. Accordingly, given the high rate of emissions from SPF (4.00 kg CO2e/M^2-R_{SI-1}) that causes this material to be the largest concentration of embodied carbon emissions by material in the study as shown in Figure 6, these three applications are consistently among the highest, if not the top three highest, concentrations of embodied carbon emissions across the HPwES program on an annual basis – see Figure 5. This indicates a region of the building to target for embodied carbon emission reductions with alternate material selections to achieve comparable insulation improvements.

Conclusions

Reducing the total carbon impact of our existing housing stock through weatherization practices is of critical importance. This must be inclusive of up-front embodied carbon emissions; material substitutions favoring those with limited embodied carbon emissions or with carbon storage values, and limiting those with high embodied carbon emissions to select applications, will be imperative to reach the climate goals established by the State of Vermont. It is clear from the results of the study that certain applications readily lend themselves to this strategy, such as the prevalence of cellulose insulation in open attics, whereas others tend to see more emissions-intensive materials commonly used, such as the use of various foam insulations across different basement applications – see Discussion above. In many cases, it is impractical to make material substitutions without dramatically increasing project costs or risking moisture damage, and there are practical realities that govern material selection in weatherization projects that frequently take precedence over climate impact. Opportunities do exist, however, to reduce embodied carbon emissions through material substitution in certain applications.

Recommendations for Reducing Embodied Carbon in Weatherization Practices in the HPwES Program

The following recommendations offer strategies for reducing embodied carbon in HPwES projects, without imposing significant compromises on program and project costs or building durability:

1) **Convert 90% of the non-cellulose material selection for open attics to loose-fill cellulose. This will result in an average annual reduction of 37% of embodied carbon for each year's worth of applications.**

   This requires a 14% increase in cellulose applications, and an 8% reduction in closed-cell spray polyurethane foam applications. This figure recognizes that approximately 10% of projects will not have sufficient access to allow for an installed depth of cellulose equivalent to that of closed-cell spray foam. This assumes that air-sealing services are achieved by caulking, targeted use of one-part spray foam, air-sealing tapes, gaskets, and/or air-tight membranes. Note that use of two-part spray polyurethane foam (SPF) "froth pack" kits for air-sealing frequently use a much higher-emission HFC-type foam, and in general encourage more general use of SPF in the attic, along with the practice of "skim coating" the attic floor with SPF as an air-sealing strategy; these practices should also be avoided whenever possible in favor of other air-sealing strategies noted above featuring lower embodied carbon profiles. Efficiency Vermont staff involved with the administration of the HPwES program identify the conversion of open attic cavities to closed cavities and associated relocation of the insulation plane as a primary source of non-cellulose insulation in these measures; while this move can improve the efficiency of ductwork or equipment located above the previous insulation plane in the attic and/or increase useful area in the building, the impact of material choice in this application should be carefully evaluated, and low-emission strategies such as vented cavities insulated with dense-pack cellulose insulation should be prioritized.

2) **Convert 50% of XPS and spray polyurethane foam material selection for basement walls (above and below grade) to polyisocyanurate foam board (e.g. Thermax, which can remain exposed by code, or polyisocyanurate foam board covered with gypsum wall board or other ignition barrier). This requires a 42% increase in polyisocyanurate foam board, and a 40% reduction in closed cell spray polyurethane foam insulation. This will result in an average annual reduction of 35% of embodied carbon for each year's worth of applications.**

   This figure recognizes that approximately 50% of projects will be comprised of rubble wall construction or other variable surfaces unsuitable for board insulation, in tight-access environments precluding the use of foam board, or otherwise unsuitable for such a substitution.

3) **Convert 75% of total material selection for basement rim joists to dense-pack cellulose. This will result in an average annual reduction of 115% of embodied carbon for each year's worth of applications.**

   While achieving reductions in excess of 100% may seem impossible, this is reflective of the carbon storage value of cellulose, indicating a result of a net negative embodied carbon emission, otherwise valued as a net positive embodied carbon storage value. This requires a 73% increase in cellulose applications, and a 67% reduction in closed cell spray polyurethane foam insulation. This figure recognizes that approximately 25% of rim joist conditions will be treated by adjoining spray foam applications on basement walls or are otherwise unsuitable for dense-pack cellulose insulation, and that the other 75% of applications suitable for dense-pack cellulose are conditioned sufficiently (temperature and relative humidity) to avoid condensation issues.

4) **Convert 60% of material selection for closed cavity ceilings to dense-pack cellulose. This will result in an average annual reduction of 65% of embodied carbon for each year's worth of applications.**

   This requires only a 11% increase of dense-pack cellulose applications, and only a 1% decrease of closed-cell spray polyurethane foam applications, while converting other insulation materials to cellulose. This figure recognizes that approximately 40% of applications are unvented, of limited depth such as to require insulation with the highest R-value per inch, or are otherwise unsuitable for dense-pack cellulose insulation, and that the other 60% of applications suitable for dense-pack cellulose are vented and can be of sufficient depth such as to avoid a significant decrease in thermal performance.

5) **Convert 100% of the material selection for wood frame walls to dense-pack cellulose. This will result in an average annual reduction of 221% of embodied carbon for each year's worth of applications.**

As with Recommendation 3, achieving a reduction in excess of 100% is reflective of the carbon storage value of cellulose, indicating a result of a net negative embodied carbon emission, otherwise valued as a net positive embodied carbon storage value. This requires a 56% increase in cellulose applications. This recognizes that there will be an appreciable reduction of thermal performance (upwards of 45% in certain cases where cavity depth is fixed and no additional insulation can be added, based on the change in material R-value/inch - R-6.6/inch for SPF vs R-3.56 for dense-pack cellulose) when compared to the use of closed-cell spray foam; this reduction in performance was taken into consideration in calculating embodied carbon emission reductions for converting foam applications to cellulose applications. Further analysis of the operational emissions increase as a result of this material conversion based on net operational fuel increase would need to be conducted to validate the net improvement of climate impact of this substitution. Ideally, this move would be in concert with an increase of cavity depth or addition of continuous low-emission board insulation to maintain the thermal performance of the assembly.

All annual emission reduction values are based on average annual emissions between 2012-2016, as provided within the data set available for this analysis. Further study may be warranted to improve reduction projections based on forecasting trendlines beyond the scope of this study.

Opportunities for further research

Although this report lays significant groundwork for selecting appropriate building materials for reducing embodied carbon emissions, further research could determine the point at which a retrofit project realizes net positive CO_2e savings when accounting for both embodied carbon and operational carbon savings.

The time it takes for operational carbon emissions reductions to fully offset the embodied carbon emissions from weatherization projects will depend on material selection and the extent of the energy reduction realized by the energy efficiency measure and by the fuel use for heating the building.

Comparing that time gap can inform material choices at the outset of a project, to maximize carbon benefit. The larger the time gap, the less likely the measure will be appropriate for realizing near-term carbon emission reduction targets. This phenomenon highlights the importance of the “time factor” of carbon; that is, embodied carbon emissions are released immediately, whereas operational carbon reductions are realized annually, accruing over time. A future research effort could use embodied carbon data from this study to compare with project-level operational carbon reduction data; the comparison could help establish strategies for net emission reductions, and thus determine the extent to which new practices can contribute to Vermont’s meeting its energy and climate targets.[10]

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[10] Vermont’s climate goals are contained in the state’s *2016 Comprehensive Energy Plan*, which adjusted 2006 goals to the following: 40 percent reduction in 1990 GHG levels by 2030; and 80 percent to 90 percent reduction in 1990 GHG levels by 2050. For comprehensive information on Vermont’s climate change goals, see the Climate Change in Vermont webpage: https://climatechange.vermont.gov/vermonts-

Appendix

Insulation materials used in building assemblies: 2013-2015

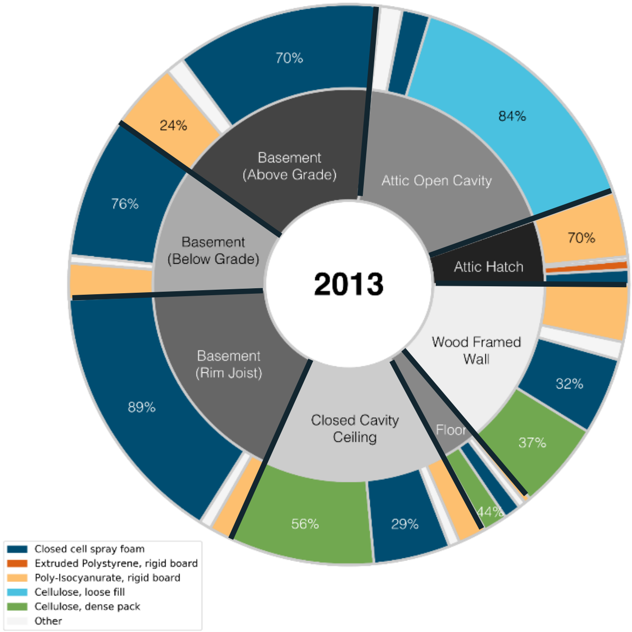

Figure 7: Types of insulation used to retrofit residential building assemblies- 2013

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goals#:~:text=The%20goals%20legislators%20adopted%20in,a%2075%25%20reduction%20by%202050.&text=These%20goals%20are%3A,below%201990%20levels%20by%202050.

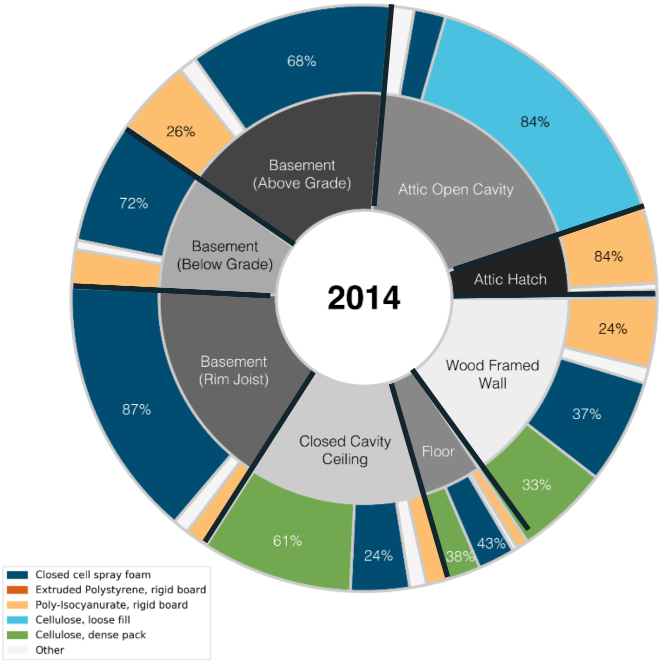

Figure 8: Types of insulation used to retrofit residential building assemblies- 2014

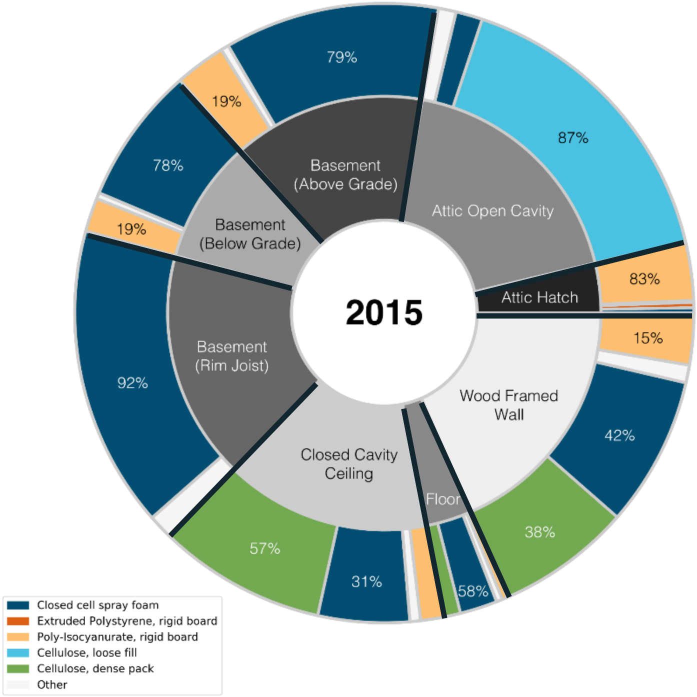

Figure 9: Types of insulation used to retrofit residential building assemblies- 2015