2019 Greenhouse Gas Taskforce

EFFICIENCY VERMONT REPORT

Efficiency Vermont

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Introduction

Each year, Efficiency Vermont sets aside a small portion of its budget to explore topics that could lead to new energy efficiency program services. This applied research and development has historically resulted in new program designs for technologies and specialized services. Projects tend to demonstrate new uses of technology, offer different types of data analysis, explore the value of non-energy benefits, and investigate cross-over opportunities with other sectors.

In 2019, Efficiency Vermont established a Greenhouse Gas Taskforce to assess new and innovative greenhouse gas reduction strategies related to energy efficiency with the potential to influence manufacturing and supply chain processes for efficient products, and Vermont-business and building-level greenhouse gas footprint calculations and incentive programs. Six research and development projects were identified and conducted:

1. Targeting of heating fuels
2. Home heating in an average house
3. Lifecycle analysis of advanced wood heating vs. oil
4. Residential construction materials
5. Natural refrigerants in commercial applications
6. Refrigeration liners

Each project is the result of a competitive internal Efficiency Vermont selection process and is grounded in staff field experience and knowledge of policy, emerging trends, and cross-sector thinking.

The following section offers a high-level summary of the projects and detailed project reports are provided in the Appendices.

The Projects

Targeting of "Dirtier Fuels" for Heating

Damon Lane, Lead Analyst

Vermont's greenhouse gas (GHG) emissions are concentrated in the transportation and heating sectors. The cold climate and the relatively high use of heating oil drive most of the heating emissions, compared to the use of wood, natural gas, propane, kerosene, and electric heat. This study investigated the extent to which an efficiency program could target customers for thermal efficiency and heating system upgrades in the context of *carbon emissions intensity* of the customer's home heating fuel.

Purpose of the project: To scope, from published data, where in Vermont Efficiency Vermont could target specific customers for energy efficiency programs, depending on the customer's primary household heating fuel, in an unregulated heating fuel market.

Results: Fossil fuels commonly used for heating in Vermont vary in GHG emissions intensity. Of the three main fuels used in Vermont (natural gas, fuel oil and propane), natural gas has the lowest emission factor per unit of heat, not counting methane leakage associated with hydrofracking. The hydrofracking method of extraction produced 67% of the nation's supply of natural gas in 2015. Further, published data on individual households are not available. Although aggregate data at the county level are available, that data is not specific enough to allow specific customer targeting for efficiency programs based on household heating fuel. Using the county data, the study showed that among fuel oil, propane, and natural gas, heating fuel oil emits 27% more kilograms of CO_2 per MMBtu of heat than natural gas. Propane produces 16% more emissions than natural gas. More granular data would inform a more accurate assessment of these fuels' emissions in Vermont.

Home Heating in an Average House

Michael Fink, Energy Data Analyst
Asa Parker, Senior Technical Energy Analyst

The project team sought to estimate real-world carbon emissions from different residential heating methods used in Vermont. Efficiency Vermont's energy efficiency programs use information about carbon emissions from fossil fuels to spur sales of heating methods that use other fuels, to advocate for cleaner technologies, or to inform policy makers of various energy uses and the associated GHG impacts. This study took the additional step of calculating longitudinal impacts from estimated average household heating use across a winter season in Vermont.

Purpose of the project: To estimate real-world carbon emissions from different heating methods used in Vermont. Information from this study could increase Vermont policy makers' understanding of the role home heating plays in Vermont's total energy landscape.

Results: Cordwood heating is nearly always a lower source of emissions relative to cold-climate heat pumps, given current data. However, other considerations such as lifecycle costs and acquiring more complete data could change those results. The study needs another generation of investigation to produce more valid and reliable results.

Lifecycle Analysis: Advanced Wood Heating vs. Oil

Lauren Morlino, Emerging Technologies and Services Manager
Adam Sherman, Senior Consultant
Bill Karis, Energy Consultant

Reducing GHG emissions has emerged as a high priority for improving building construction and maintenance practices. Most data to date have looked at energy-associated emissions from a product's lifecycle, once the product is in use. This report examines the emissions impacts of additional phases in the full lifecycle, from manufacture to the delivery of the product to a home or business. It compares the emissions related to the path to installation, emissions embedded in fuel production and delivery, and the emissions while in use.

Purpose of the project: To give Efficiency Vermont a model for completing lifecycle analysis calculations, across additional phases of a product's life, and thus to create methods for developing future lifecycle analysis protocols for systems for which Efficiency Vermont offers incentives.

Results: Specific and comparable lifecycle emissions data was difficult to find for this analysis. Using the information available, the lifecycle analysis found that the oil boiler and fuel would emit 98 metric tons of CO2e over 20 years. The wood pellet boiler and pellet fuel would emit 16 metric tons CO2e over 20 years.

Construction Materials

Brian Just, Manager, Engineering

The manufacturing of building materials accounts for 11% of global carbon emissions. The GHG emissions from extraction of raw materials, through the manufacturing and transportation of building products, can be so significant that the building's construction materials equate to decades of emissions from building heating and cooling and other operations. This paper considers ways to use thoughtful design and materials that reduce GHG emissions—and even store carbon. It investigates current standards for quantifying product emissions impacts and opportunities for Efficiency Vermont programs' tracking of carbon use associated with building materials.

Purpose of the project: To offer responses to two research questions:

(1) What are the GHG impacts of residential building materials commonly used in Vermont?
(2) What influence could Efficiency Vermont have if it encouraged the use of materials with lower GHG emissions in the building projects it incentivizes?

Results: Environmental product declarations are lacking in data and require tedious conversions for comparing across products. Using data available, fiberboard is by far the best performer in terms of average kilograms (kg) of emitted CO_2e per 100 square feet of R-20 insulation (-259.7). The next-best performing material is densepack cellulose, with -88.6 kg of emitted CO_2e, indicating the capability of both of these materials to store carbon.

Natural Refrigerants

Lauren Morlino, Emerging Technologies and Services Manager
Ali White, Energy Consultant

Managing refrigeration in commercial settings is considered a top opportunity for mitigating climate change. In addition to sourcing refrigerators and chillers that are more efficient than standard and old models, efficiency programs are starting to look for opportunities to curtail refrigerant leakage—a condition that is seldom enforced in Vermont. This report investigates the alternative market for refrigeration, comparing systems that responsibly use the natural refrigerants CO_2, hydrocarbon, and ammonia for various applications, particularly in grocery stores.

Purpose of the project: To determine the GHG savings associated with a large grocery store's natural-refrigerant CO_2 rack (refrigeration system that contains several compressors in a row, cycling on and off to provide 24-hour refrigeration), beyond the GHG savings directly associated with electrical efficiency savings from an efficient refrigeration product.

Results: The GHG reductions in terms of refrigerant emissions: 30,900 metric tons of CO_2e (20 years) far outweigh the GHG reductions in terms of emissions from energy use: 6,780 metric tons CO_2e (20 years).

Refrigeration Liners

Lara Bonn, Emerging Technologies & Services Director

Bioplastic refrigerator liners manufactured by NatureWorks claim to have better long-term energy performance and a lower carbon footprint than traditional plastic refrigeration liners. These liners have large market potential and offer significant energy benefits because of the number of refrigerators in Vermont and the potential for an electric product reducing GHG emissions. Since every household is expected to have at least one refrigerator, making natural liners a market standard would decrease emissions, energy use, and energy cost over a fridge's lifetime.

Purpose of the project: To scope, from published data, where Efficiency Vermont could quantify energy savings and carbon savings from switching energy efficient refrigerators to using the NatureWorks bioplastic liner.

Results: Lara Bonn worked closely with NatureWorks to receive product information in an effort to do calculations on energy and carbon savings. Unfortunately, despite willingness to sign an NDA and coordination over more than a year about this project, Lara was not able to receive the needed data to complete this project during the allotted R&D calendar year timeframe.

Appendix 1: Targeting Heating Fuels by Green House Gas Emissions

Author: Damon Lane

Introduction

Vermont's GHG emissions are concentrated in the transportation and heating sectors. The heating emissions are driven by the cold climate and the high share of oil heating compared to the rest of the country. Vermonters also use wood, natural gas, propane, kerosene and heating. This investigation was conducted to determine if there is an effective way to target customers for thermal efficiency and heating system upgrades by the carbon emissions intensity of the customer's home heating fuel for the most commonly used heating fuels in Vermont.

Research Question

Can Efficiency Vermont use published data to target specific customers for energy efficiency programs based on primary household heating fuel in an unregulated heating fuel market?

Available Data

All heating fuels, except for natural gas, are unregulated in Vermont leading to a gap in available data on location-specific consumption. The U.S. Census provides heating fuel use by geographies down to the census tract level. The census data differentiates owners and renters, who have different paths to heating upgrades. This information can be useful in program design and targeting.

Ample data exists regarding emissions for different heating fuels, though the emission factor for natural gas needs to be updated (increased) to account for modern production techniques.

Findings

The fossil fuels commonly used for heating vary in greenhouse gas emissions intensity. Of the three main fuels used in Vermont, natural gas has the lowest emission factor, although that factor has not been updated to account for the methane leakage associated with hydrofracking. Hydrofracking produced 67% of the nation's natural gas in 2015.[1] Ignoring the methane leakage associated with natural gas hydrofracking[2], heating fuel oil produces 27% more CO_2e emissions per unit energy than natural gas, and propane produces 16% more, as shown in Figure 1..[3]

[1] EIA, 2016. "Hydraulically fractured wells provide two-thirds of U.S. natural gas production," https://www.eia.gov/todayinenergy/detail.php?id=26112
[2] Alvarez, et al., estimate methane emissions for U.S. 2015 natural gas supply to be 60 percent higher than the U.S. Environmental Protection Agency inventory estimate.
Alvarez, R., et al., 2018. "Assessment of methane emissions from the U.S. oil and gas supply chain," *Science*. Vol. 361, Issue 6398, pp. 186-188. https://science.sciencemag.org/content/361/6398/186
[3] EIA, 2016. "Carbon Dioxide Emissions Coefficients," https://www.eia.gov/environment/emissions/co2_vol_mass.php

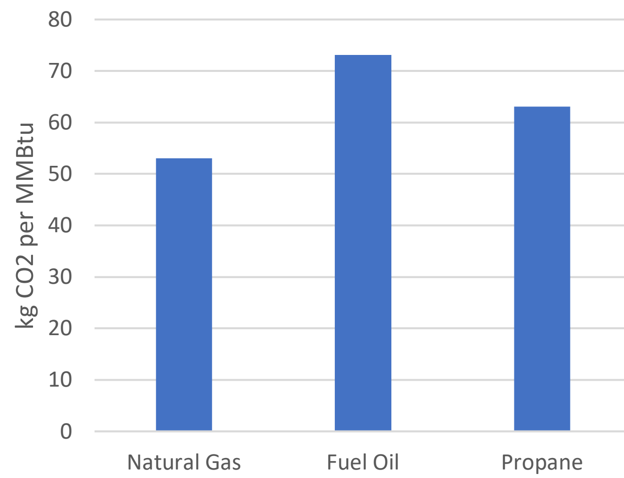

Figure 1: GHG Emissions per unit of heat by fuel.

Table 1 lists the percentage of households in Vermont counties using each fuel as the main home heating fuel. Each county sums to 100%; secondary heating fuels are not accounted for in the data. Chittenden and Franklin counties stand out because of the natural gas networks servicing those counties.

Table 1. Share of Heating Fuel by County in Vermont [4]

	Utility Gas	Propane	Electricity	Fuel Oil	Wood
Rutland	2%	14%	4%	64%	14%
Orleans	1%	15%	1%	52%	28%
Grand Isle	1%	22%	2%	52%	20%
Orange	1%	23%	2%	43%	29%
Chittenden	58%	10%	9%	16%	5%
Lamoille	2%	25%	3%	46%	21%
Windsor	3%	22%	5%	49%	19%
Caledonia	1%	18%	1%	53%	23%
Windham	2%	16%	5%	52%	22%
Addison	2%	24%	3%	50%	19%
Washington	2%	24%	5%	49%	18%
Franklin	27%	12%	2%	41%	17%
Bennington	2%	14%	4%	63%	13%
Essex	1%	10%	1%	55%	30%

[4] U.S. Census Bureau, 2014-2018. American Community Survey 5-Year Estimates, B25040: House Heating Fuel https://censusreporter.org/data/table/?table=B25040&geo_ids=04000US50,050|04000US50&primary_geo_id=04000US50

As mentioned previously, the county-level share of heating fuel data is available on smaller geographies and by tenancy, though choosing smaller populations of data means it may not be as accurate, or other dimensions, such as the year, need to be broadened to maintain adequate sample size.

Results

No-go decision

In consultation with Efficiency Vermont's marketing data analysis team, the project team decided the available data was insufficient to target energy efficiency programs towards households that are using dirtier heating fuels. The data shows a mix of fuels used within a small geography, but not which household is using which fuel. While marketing content could focus on certain fuel types, there is not enough geographic variation to make it worth sending such content to some parts of the state and not others.

Conversely, Efficiency Vermont can use other marketing techniques to target anyone using fossil fuels. Other considerations, such as the customer's ability and propensity to act, may be more important than the heating fuel mix in the Census Tract or county.

Appendix 2: Calculated Carbon Emissions from Heating through the 2018-2019 Vermont Winter

Authors: Michael Fink and Asa Parker

Introduction

What residential space-heating method creates the smallest carbon footprint, in a region where winters are long and can involve deep freezes, thaws, and prolonged periods of below-freezing temperatures? This project compared the carbon footprints of different heating methods for the 2018–2019 winter in Burlington, VT, for a typical residence. The study investigated wood heat, several electric methods, and fossil fuels heating; calculating loads and carbon dioxide ($CO_{2)}$ emissions at 15-minute intervals for the entire heating season.

Results show cordwood heating is nearly always a lower carbon emission source[5] of heat during the winter relative to cold-climate heat pumps. Geothermal heat and cordwood heating are comparable as CO_2 emitters. However, the study also showed that the results run a high risk of being skewed if the emissions conversion factors are inaccurate. Appendix I summarizes the conversion factors for different source fuels, offering the conditions for drawing conclusions about specific applications of the various heating methods. The author welcomes reader critique on the conversion factor calculation methodology for future refinement.

Specific Aims

This research and development project sought to estimate real-world carbon emissions from different heating methods used in Vermont. Although information about carbon emissions from fuels has been used to spur sales of certain heating methods, to advocate for cleaner technologies, or to inform policy makers of various energy uses and the associated greenhouse gas impacts, this study pursued longitudinal impacts from average residential use of heating fuels in a single city.

Background and Significance

Most calculations of residential carbon footprints are likely to contain estimates of total per capita energy use from some combination of transportation, heating and cooling, human diet, recycling, and production of waste.[6] Home heating fuel is widely considered to be a significant carbon emitter, particularly during winter months in a cold climate. However, with the expansion of "clean-energy" heating equipment and methods, there has been no other exploration to date from longitudinal estimates of carbon footprints of these and traditional home heating methods, particularly in regions that experience significant winter seasons, with spikes in temperature, and occasional prolonged periods of cold weather.

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[5] As measured by CO_2 emissions. Particulate and other emissions were not calculated in this study.
[6] See, for example, the interactive World Bank site showing nation-by-nation information CO_2 emissions: Oak Ridge National Laboratory, 2014. "CO_2 Emissions (Metric Ton per Capita)." Oak Ridge, Tenn.: Carbon Dioxide Information Analysis Center, Environmental Sciences Division. https://data.worldbank.org/indicator/EN.ATM.CO2E.PC. See also a mainstream interpretation of those data: Kinhal, Vijayalaxmi, n.d. "What Is the Average Carbon Footprint?" LovetoKnow.com. https://greenliving.lovetoknow.com/Define_Carbon_Footprint.

The analysis from this study can contribute to Vermont policy makers' understanding of the role home heating plays in Vermont's total energy landscape. The calculation methods can also be a model for other jurisdictions interested in understanding local residential heating carbon footprints, particularly as policy makers come to accept greenhouse gas emissions as the standard indicator of climate change and their role in global temperature rise.[7]

Methods

Efficiency Vermont researchers obtained data on an "average" house's space heating use during the study period, beginning with the first heating degree day after August 2018, and ending with the last heating degree day in the first half of 2019. The study team applied 15-minute interval weather data for that 2018–2019 winter in Burlington, to obtain near real-world weather normalization for the analysis.

The "Average House" and Assigned Values

The "average house" comes from a Vermont Residential Heating Analysis conducted by Russell Meyer and Tom Mauldin of NMR Group (memo from Meyer and Mauldin to Brian Cotterill of Vermont Public Service Department in February of 2017). Among 12 houses in the cohort, the average conditioned floor area is 2,035 square feet with an average total annual space heating consumption of 106 million BTU.

Time-of-Day Adjustments

The carbon footprint of any heating fuel will vary with changes to outdoor temperature, the occupancy, and the behavior of the occupants.

This study attempted to account for time-of-day and day-of-week data by using adjustment factors found by the Cadmus Group in an analysis of residential heating.[8] The Cadmus Group report gave the study team confidence in making an "adjustment loadshape" that scales up and down slightly, depending on the day of week. Figure 2 shows what those adjustment factors look like for each day of the week. The blue line indicates the loadshape for a winter Sunday (the gray lines are other days of the week).

[7] Global temperature rise is the central threat to natural and human systems, according to the Intergovernmental Panel on Climate Change. See IPCC, 2015. Special Report on Global Warming of 1.5°C. https://www.ipcc.ch/sr15/.
[8] Walczyk, J., 2017. "Evaluation of Cold Climate Heat Pumps in Vermont," https://publicservice.vermont.gov/sites/dps/files/documents/2017%20Evaluation%20of%20Cold%20Climate%20Heat%20Pumps%20in%20Vermont.pdf

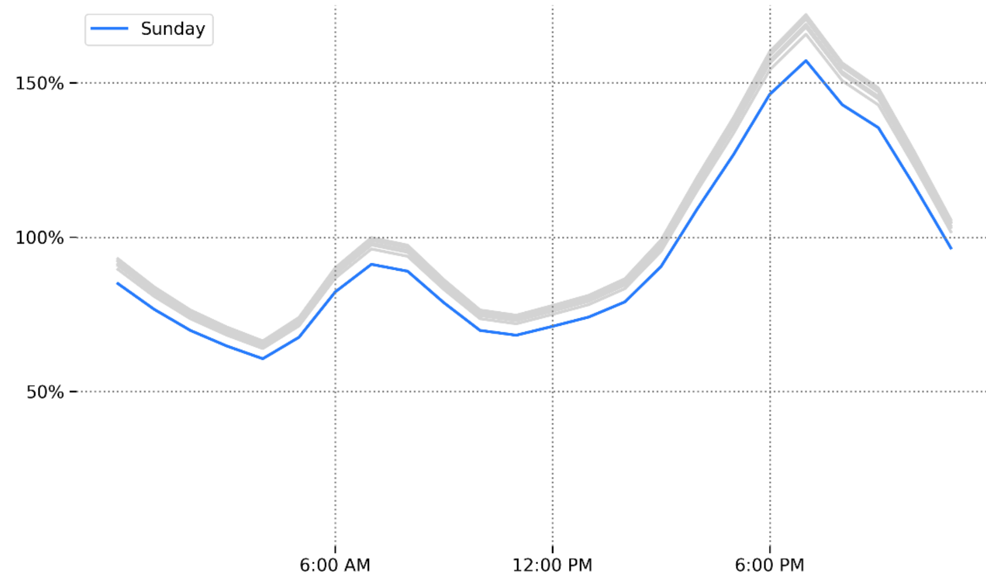

Figure 2. Daily pattern of heating load in Vermont, during the winter.

For example, if otherwise it had been calculated that 1,000 BTU were needed for the 15-minute period starting at 6:00 p.m. on a Sunday, that number is multiplied by about 1.5 to account for the varying day-of-week and time-of-day demand for heat.

The following method was then used to determine carbon footprints for each 15-minute period of the 2018-2019 winter:

1. Use a defensible "typical" value for total heat energy needed for an average house throughout the winter.
2. Find a "heat energy needed" value for each 15-minute period.
    a. Build a day-of-week / hour-of-day heating energy curve using the Cadmus Group's cold-climate heat pump (CCHP) research.[9]
    b. Assign a balance point and assume heating is required if the outdoor temperature is below the balance point.[10]

[9] Absent any other good source, the research team recognizes the limitations of assuming the cold-climate heat pump (CCHP) heating curves discovered by the Cadmus Group offer a reliable representation of how other fuels might be used:

1. A CCHP device is almost infinitely variable in its output, whereas an oil furnace or woodstove is much less controllable.
2. It is assumed that all other heat sources have day-of-week / hour-of-day patterns similar to those of a CCHP. In the real world, this assumption is probably overstated. For example, woodstoves require greater attention by the household and are less likely to be used on weekdays than weekends, whereas the opposite is probably true for CCHPs, which require little or no attention.

Nevertheless, it is still a useful exercise to examine the relative emissions, if each fuel source is asked to produce identical heat for all 15-minute periods for the winter. See Korn, D., Walczyk, J., and Jackson, A., 2018. "Evaluating Cold Climate Heat Pumps: Understanding How and Where Cold Climate Heat Pumps Can Displace Less Efficient Heating Sources." *Proceedings of the 2017 International Energy Program Evaluation Conference.* https://cadmusgroup.com/wp-content/uploads/2018/03/Cadmus-Cold-Climate-Heat-Pumps-IEPEC-2017-DK-JW-AJ-1.pdf.

[10] 60°F was used for the heating balance point for all calculations.

c. Assign a "trailing period" length to determine required heating load. The average outdoor temperature over the previous 4 hours was used to calculate heating energy needed for the current 15-minute period.

d. Assume that heat energy needed is proportional to the difference between the "trailing period" outdoor temperature and the balance point.

3. Portion out the "average house's" needed heating energy for the entire year into 15-minute periods according to the "heat energy needed" for each 15-minute period found in the previous step:

$$Heat\ energy\ needed = A_{tow} * \left(\frac{DD_{current\ period}}{DD_{entire\ winter}}\right) * E_{total}$$

Where A_{tow} is the day-of-week adjustment factor from the Cadmus Group heating study,[11] *DD* is the degree-days for the current period and for the entire winter, calculated with the 60° balance point, and E_{total} is the total heat energy used by our average house in the 2018-2019 winter.

4. For all non-electric heating sources, determine the 15-minute period emissions for the entire 2018-2019 winter: the heat energy needed, multiplied by a conversion factor tied to the emissions for that particular fuel (*emissions factor*). For example, to find the emissions for a fuel oil furnace for a 15-minute period when 8,800 BTU of heat energy were required:

$$CO_2\ emissions = \ emissions\ factor * heat\ energy\ needed$$
$$644\ g\ CO_2 = 0.0732\ \frac{g\ CO_2}{BTU} * 8{,}800\ BTU$$

5. For electric-based sources of heat with constant coefficients of performance (COP; for example, resistance heating or geothermal), multiply heat energy needed by current emissions of the electric grid and divide by the COP. For example, for a 15-minute period with 8,800 BTU needed, the grid fuel mix footprint is 230 grams CO_2 / kWh and the system COP is 4.1. The calculation to find emissions for the 15-minute period in question is then:

$$\frac{8{,}800\ BTU * 0.000293 \frac{kWh}{BTU} * 230\ \frac{g\ CO_2}{kWh}}{4.1} = 145\ g\ CO_2$$

6. In the case of CCHPs, the calculation is identical to that outlined in Item 5, except that the COP is interpolated from the Cadmus analysis of actual, observed typical cold-climate heat pump COP values to outdoor temperatures.

General Results

Whole Winter Summary

Figure 3 compares the calculated winter-long emissions from eight different fuels in the modeled "average house" in Vermont. The lowest calculated footprint for the 2018-2019 winter was from heating using cordwood. Unsurprisingly, coal, oil, propane, and natural gas all had much larger carbon footprints. Perhaps surprising: a geothermal system with a COP of 4.1 had a higher carbon footprint than cordwood.[12]

[11] Walczyk, J., 2017. "Evaluation of Cold Climate Heat Pumps in Vermont," https://publicservice.vermont.gov/sites/dps/files/documents/2017%20Evaluation%20of%20Cold%20Climate%20Heat%20Pumps%20in%20Vermont.pdf

[12] It should be noted that the carbon footprint of electricity used for heating was derived from ISO New England's fuel mix, which includes several energy generation source fuels not used in Vermont. That is, the modeling in this study does not use Green Mountain Power's (GMP's) energy generation fuel mix or that of any other Vermont distribution utility due to lack of available data. GMP reports being 90

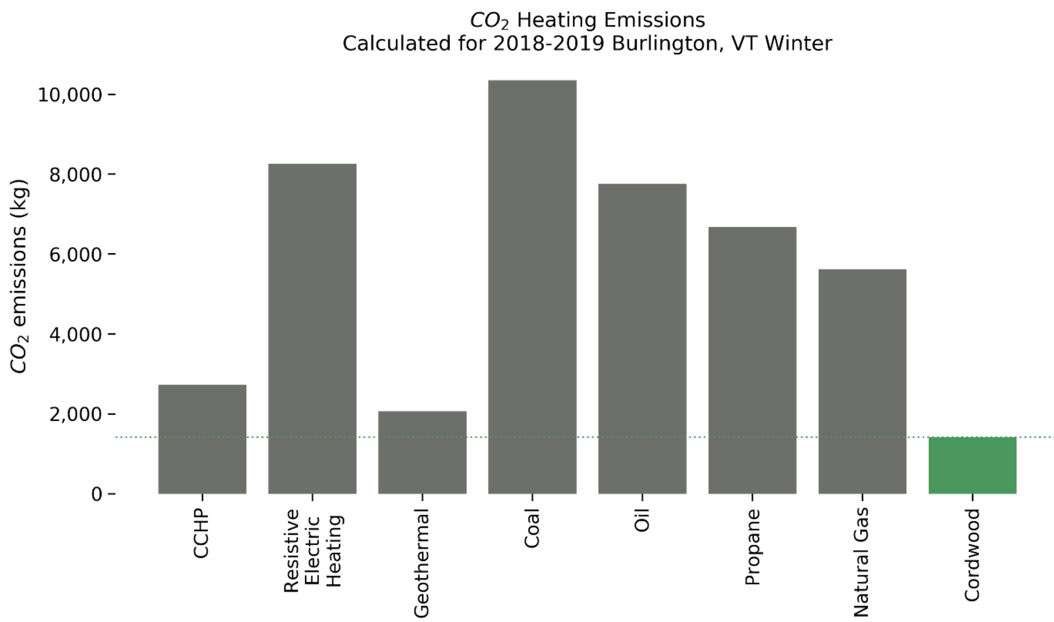

Figure 3. CO_2 emissions from eight heating sources in use in Vermont.

CCHP vs. Cordwood by Outdoor Temperature

Cordwood's emissions advantage over CCHPs in this study varies significantly in terms of outdoor temperature and grid "cleanliness." At cold temperatures, the efficiency of wood heating is little changed, but CCHPs become less efficient using more energy to produce heat. Additionally, at cold temperatures the grid typically becomes more carbon intensive, because grid operators substitute oil for natural gas at critically cold temperatures. Figure 4 summarizes this effect by showing the average daily emissions for both cordwood and CCHPs, after categorizing the days by temperature. Note that although the increase in cordwood emissions across the categories looks roughly linear, the CCHP relationship with emissions is superlinear.

percent "low carbon", whereas the New England grid's fuel mix is closer to 35 percent "low carbon." It is likely that if this study's calculation were to be run again, using emissions factors for GMP's electricity contracts, geothermal and cold-climate heat pumps would be cleaner than cordwood.

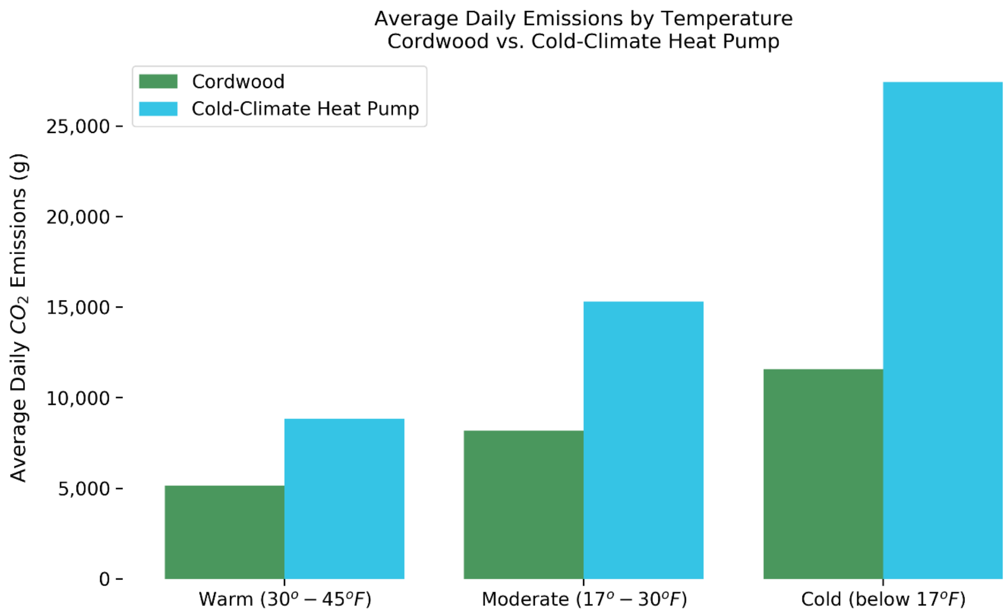

Figure 4. Average daily emissions for cordwood and CCHPs, depending on outdoor temperature.

Footprint "Emission shapes" on Weather-Interesting Days

Emission shapes—the day-long pattern of emissions entering the atmosphere from an emissions source—vary considerably by fuel. **Figure 5** shows this study's modeling of four popular heat sources for the average house, on the coldest day of the 2018-2019 winter period (January 21, 2019).

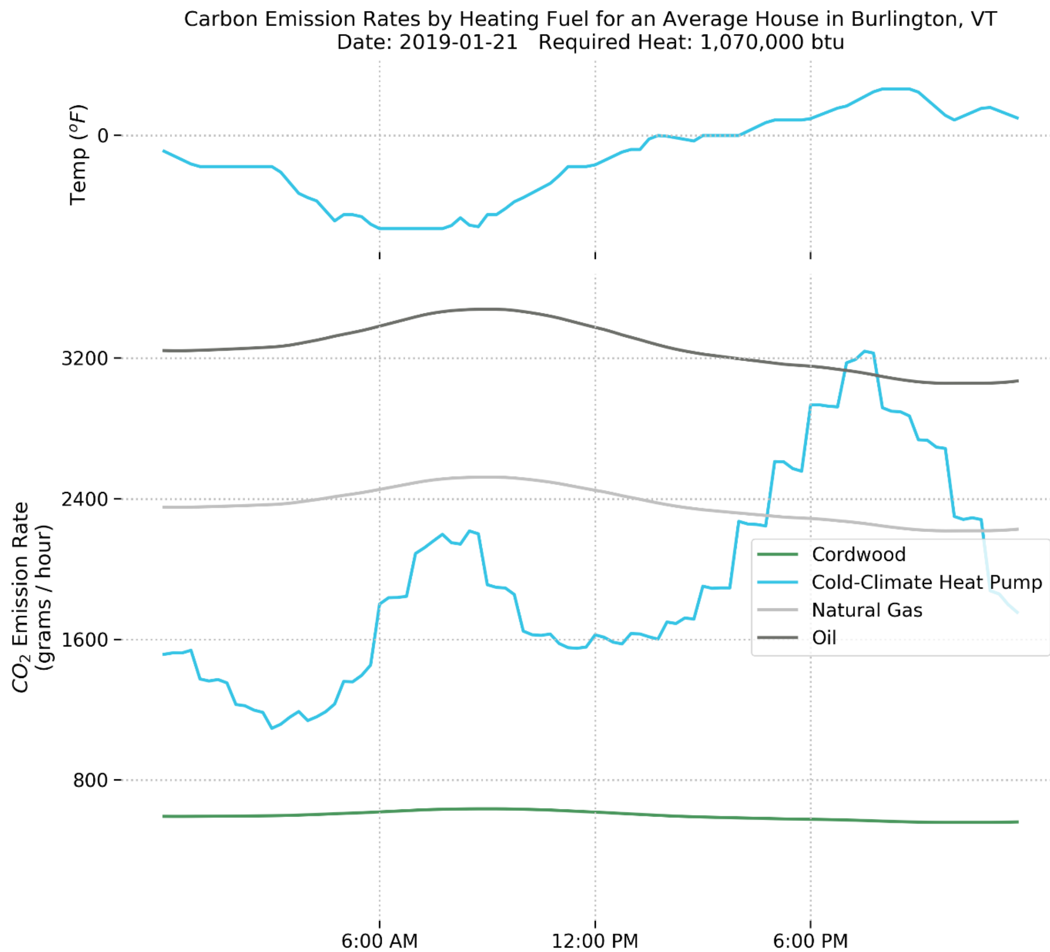

Figure 5. Modeled emission shapes for cordwood, cold-climate heat pumps, oil, and natural gas, across the 24-hour period of the highest heating degree-day in the 2018 - 2019 winter period.

On no other day is cordwood a bigger winner than on this especially cold day. It saves more than 20 kg of CO_2 emissions, relative to the CCHP; and nearly 60 kg, relative to fuel oil.

Regarding the emissions shapes, the CCHP is usually the second cleanest source of heat. However, during the evening peak (when the electric grid is at its "dirtiest"), it is slightly dirtier than natural gas and even oil. Further, the CCHP also suffers from its weakest COP of the entire winter, on the coldest day. Despite the weak coefficient of performance, it is still cleaner than using natural gas or oil across the whole day.

Figure 6 compares each heat source's emissions on that coldest day.

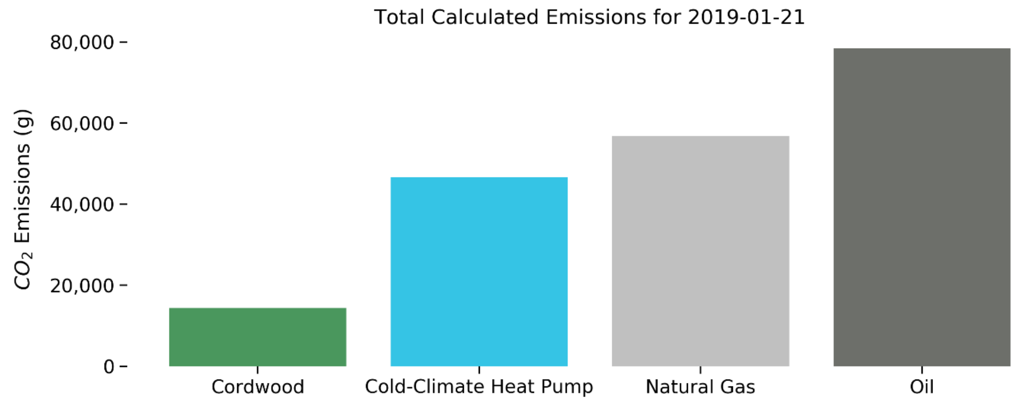

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Figure 6. Modeled emissions for four heat sources, on the 2018-2019 winter season's coldest day in Burlington, VT.

Figure 6 shows the emissions shape for the "cleanest"[13] fuel mix day that had an average temperature below 30°F, February 10, 2019. The CCHP fares much better relative to cordwood heating on this day, although it still is responsible for slightly more emissions. In this case, it is certain that if the study had used GMP's fuel mix instead of ISO New England's, the CCHP would be much cleaner than cordwood.

[13] ISO-NE publishes the ISO-NE grid's 15-minute fuel mix and daily fuel mix. The study examined all the days that were below 30 degrees (i.e. winter day with significant heating load rather than a very temperate autumn day) and found the day with the lowest average carbon footprint to use for this plot.

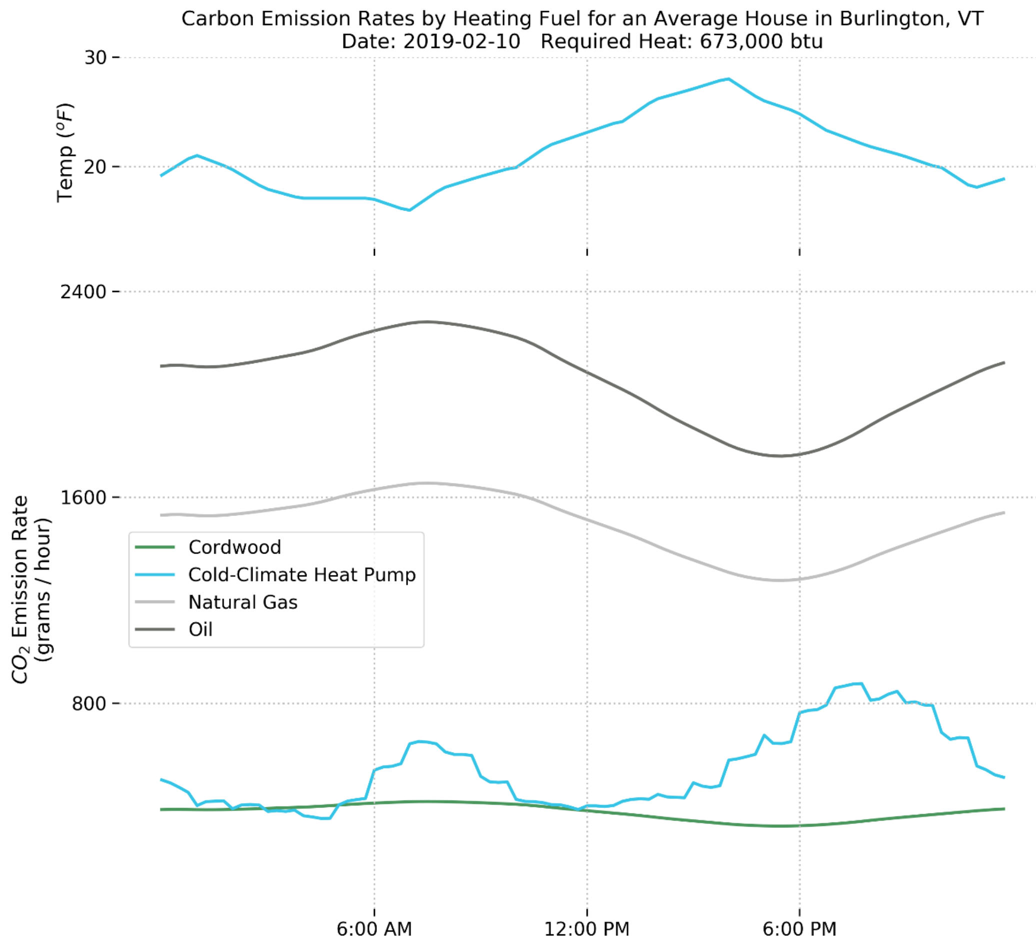

Figure 7. Heating performance for the four fuels, on a day averaging approximately 30 degrees Fahrenheit, February 10, 2019.

Figure 8 shows the total modeled emissions for that same day, by heat source.

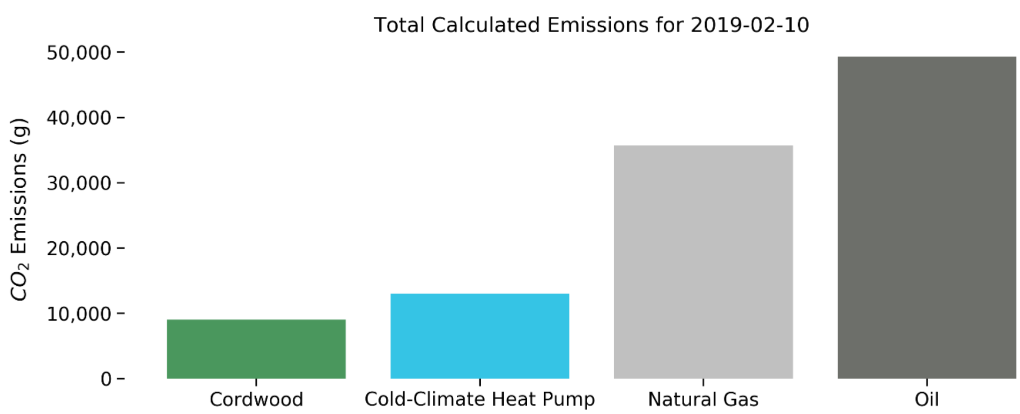

Figure 8. Total emissions, modeled for the average house's heating needs on February 10, 2019, the electric grid's "cleanest" winter day in which temperatures averaged approximately 30 degrees Fahrenheit in Burlington, VT.

By comparison, Figure 9 shows the emissions shape plot for the grid's dirtiest day, January 22, 2019.

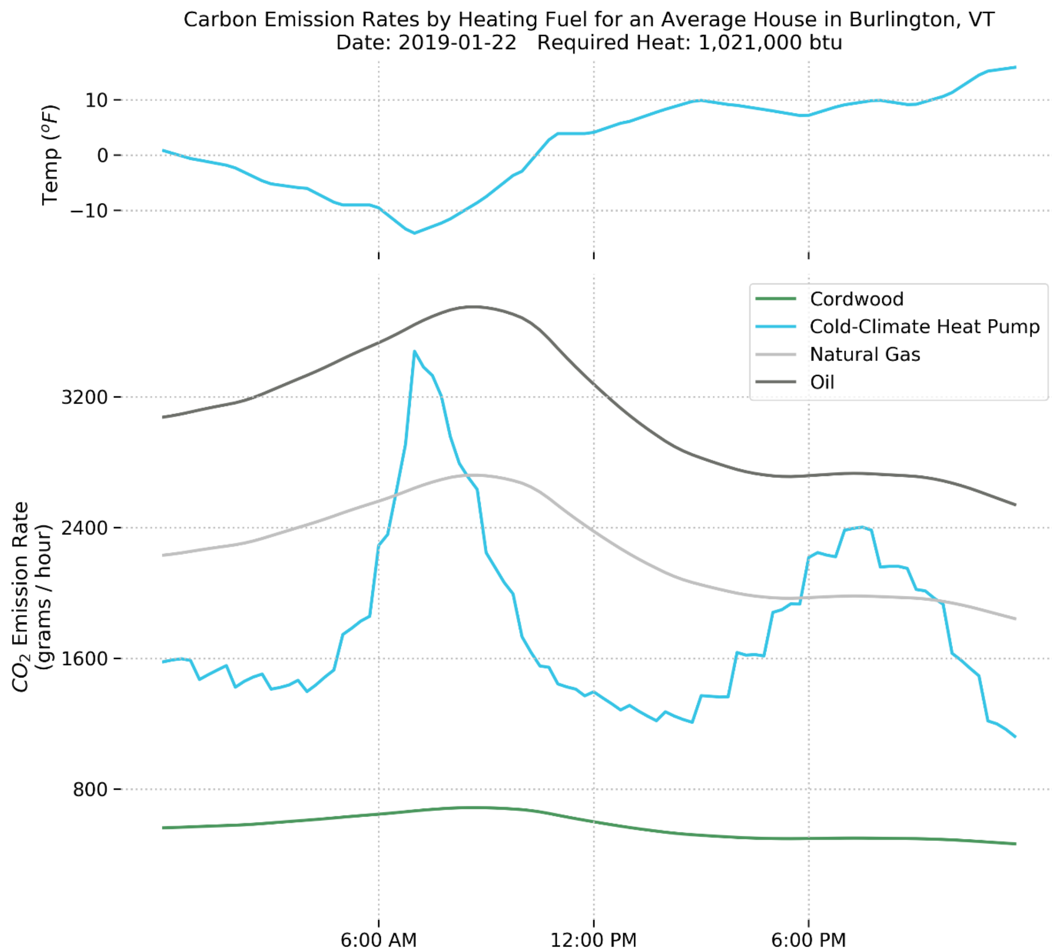

Figure 9. Modeled carbon emission rates for an average house in Burlington, Vermont, on January 22, 2019, the coldest day of the winter season.

The remarkable feature of this emissions shape is the enormous spike in emissions from the CCHP around 7:00 a.m. This results from (a) the ISO New England grid's being especially dirty (using oil for the morning peak) and (b) the especially poor COP as the temperature bottoms out at about -12°F, a temperature at which most heat pumps have a COP of about 1. Figure 9 shows the comparison of carbon emissions on that day, by heat source.

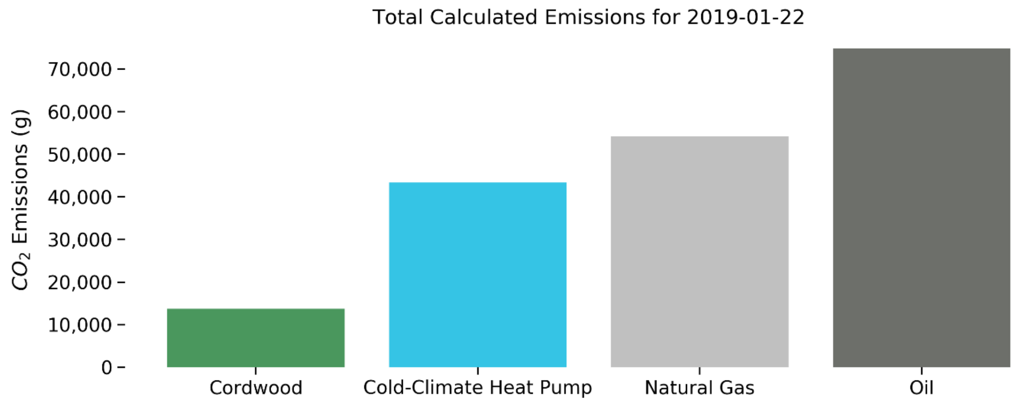

Figure 10. Comparison of carbon emissions for the average house, by heat source, for January 22, 2019, the coldest day of the year in Burlington, Vermont.

Even on this dirtiest day for the New England grid, the CCHP is still cleaner than using natural gas or oil to heat the average house.

Future Refinements for This Study

The modeling of four classical heat sources for an average house in Burlington, Vermont, presents an approach that can inform deeper and wider study. With this starting point achieved, further examinations could yield important insights about the carbon footprints of residential heating methods in both cold and warm climates.

The following research issues should be considered in any future designs that draw from this particular study:

1. All electric sources of heat (CCHPs, geothermal systems, and so on) require time-dependent fuel mix information from a local distribution utility. In trying to model a valid, real-world study, it is inappropriate to use the regional grid's fuel mix information (in this case, from ISO New England) if a local distribution utility is paying a premium for low-carbon energy.
2. The study team used data from the Biomass Energy Resource Center (BERC), which has derived the cordwood emissions factor. What considerations should a team apply to refine this figure for greater accuracy—for Vermont or any other jurisdiction?
3. Any research involving the GHG impacts must use confirmed, local ISO New England carbon emission conversion factors for the power plants that are on the Vermont grid. The calculation in this report uses simplified conversion factors that are national rough averages for power plants using a given fuel.
4. Further, targeted research on emissions from different heating fuels, to account for typical efficiencies of Vermont home furnaces, would enable more accurate reporting of the system's effects.
5. Although this study has modeled the calculations on an average-sized home in Burlington, the other real-world factors that can affect GHG emissions are very limited. Beyond square footage, future research should also consider other characteristics of an average home, such as average age of its heating system, R-values in walls and attics, presence or absence of a basement, presence or absence of backup heating systems and how often those are used, window age and likely U- or R-factors, and so on.

Appendix I: Conversion Factors / Sources

The accuracy of the results of this analysis is completely dependent on a few conversion factors and emissions factors. The research quickly revealed that data and other information to support a high level of accuracy were not available. Further, verifying the accuracy of these conversion factors was beyond the scope of this analysis. Nevertheless, the analysis offers a starting point for readers to understand the methods, and to put the results into a broad perspective, recognizing that the accuracy of the analysis still needs refinement.

To that end, Efficiency Vermont invites the reader to consider the following factors and assumptions, and to provide feedback to Efficiency Vermont about any misapplied conversion factors. Efficiency Vermont's objective is to refine the calculation with better information, so that it can be shared with greater authority—for the benefit of other programs that might want to use the calculation basis for other purposes. New conversion factors may be submitted to the authors, with the rationale and supporting information, so that the team may improve the calculation.

On the emissions of wood heating

For all conversions of wood to heat energy, the Biomass Energy Resource Center (BERC) "recommended emission rate" of 29.58 pounds / MMBtu or 0.0134 grams / BTU was used. This rate appears in the Summary of Carbon Emission Impacts of Modern Wood Heating in Northeastern US.[14] To the extent that this conversion factor needs further refinement, many of the conclusions of this study also need correction. Improving the accuracy of this conversion factor will be subject to evaluation and approval by Efficiency Vermont before new calculations can be made.

On the emissions of grid energy

To calculate the emissions associated with a unit of energy produced at a specific time, the study team used the fuel mix data provided by ISO New England's Web Services API v1.1, and converted that information to a CO_2 emissions rate, using the U.S. Energy Information Agency's (EIA) average national values as show in:

Table 2: CO_2 emissions rate by fuel type derived from ISO New England and EIA data

Fuel	CO_2 emissions (g/kWh)
Coal	820
Natural gas	490
Nuclear	12
Hydro	24
Refuse	700
Solar	45
Wind	11
Wood	230
Oil	650

The CO_2 emission value ISO New England assigns to wood burned for electricity is higher than the emission rate BERC uses for wood heating. It appears that ISO New England uses different factors in determining this value, relative to the emission impacts from using wood for home or commercial space heating. This discrepancy should be investigated, and either (1) rectified or (2) a defensible value chosen and justified for future versions of this calculation.

[14] BERC, 2016. "*Summary of Carbon Emission Impacts of Modern Wood Heating in Northeastern US,*" https://www.biomasscenter.org/pdfs/veic-carbon-emission-and-modern-wood-heating-summary.pdf

On the emissions from fossil fuel sources

The study team used EIA CO_2 Uncontrolled Emission Factors data[15] for this study.

Weather data

The study team collected weather data from the KBTV weather station at Burlington International Airport through the File Transfer Protocol server hosted by the National Renewable Energy Laboratory.

Appendix II: ISO-NE API Accessor Program

An ancillary benefit of this study was the building of a tool that allows for automated downloading of data from ISO-New England. The tool provides fuel mix data, marginal fuel source, locational marginal pricing from all regions of New England, day-ahead and real-time load information by region, and carbon footprint as calculated from the fuel mix and as calculated from the marginal fuel.

This tool will facilitate future studies of carbon emissions, energy pricing, and marginal fuel prediction, enabling Vermonters to get cleaner and cheaper energy.

The user requests a download for a specific date range and the tool makes the appropriate queries from the ISO-New England API service to return 15-minute time series data for the information and returns an Excel-readable spreadsheet.

[15] EIA, 2016. "Carbon Dioxide Emissions Coefficients," https://www.eia.gov/environment/emissions/co2_vol_mass.php

Appendix 3: Oil and Advanced Wood Heating Lifecycle Analysis for a Vermont Home

Authors: Lauren Morlino, Adam Sherman, Bill Karis

Introduction

As the building construction and maintenance industry works to reduce its contribution to greenhouse gas (GHG) emissions, distributors, contractors and customers are increasingly aware of a product lifecycle's emissions impact. Lifecycle analysis (LCA) assesses a product's environmental impacts from creation through use and ultimately disposal.

As an energy efficiency program administrator, Efficiency Vermont has the opportunity to increase awareness of a product's lifecycle impact on energy consumption and the associated carbon emissions. To date, Efficiency Vermont has focused on the energy-associated emissions impact during the use-phase of a product's lifecycle. This paper outlines the emissions impact of lifecycle phases – primary material production emissions, distribution fuel emissions, fuel extraction and processing emissions, fuel distribution emissions, and end use emissions – for two boilers – an oil combustion boiler and an advanced wood heating boiler.

Given the relatively new application of lifecycle analysis in the energy efficiency industry and the absence of complete data sets for all products and processes, the available sources of information are woven together with a series of key assumptions.

The purpose of this paper is to provide Efficiency Vermont, Department of Public Service regulators, and the interested stakeholders with an estimate of the comparative lifecycle GHG emissions of a system incentivized by Efficiency Vermont and the presumed business as usual option of heating with #2 fuel oil. Additionally, the research creates a methodology for developing future LCA protocols for other Efficiency Vermont supported systems.

Research Question

How do two heating systems, an oil boiler and an advanced wood heating (AWH) boiler, compare in embodied carbon of the equipment, the upstream emissions associated with extracting, processing and distributing fuel, and the direct emissions from onsite combustion?

Biogenic and Geologic Carbon

An important distinction to make when completing a carbon LCA is the difference between biogenic and geologic carbon emission sources. Biogenic carbon is continually in flux between plants, oceans, and trees into the atmosphere. Plants, oceans, and trees absorb and temporarily sequester carbon from the atmosphere and eventually release it– when they, or the organisms within them, die and decompose.

Geologic carbon emissions are fundamentally different than biogenic emissions. Burning fossil fuels releases geologic carbon, or carbon that took millions of years to form. Extracting geologic carbon that has been locked deep beneath the Earth's crust and emitting it, is a one-way path to increasing long-term atmospheric levels of CO_2. In absence of human activity extracting and burning fossil fuels, this carbon would otherwise remain sequestered beneath the Earth's surface and stay out of the atmosphere forever.

Figure 11 depicts the full carbon cycle including biogenic and geologic carbon. [16]

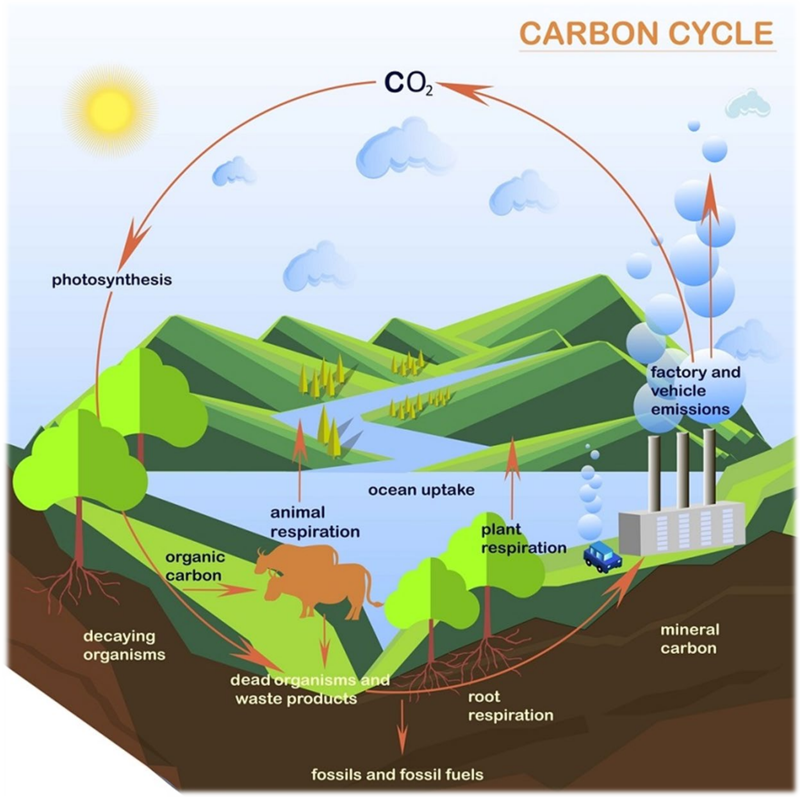

Figure 11: Full carbon cycle[16]

When considering the carbon intensity of wood versus oil fuel, biogenic versus geologic carbon must be factored differently. Therefore, the analysis below accounts for the geologic sources of CO_2 equivalent (CO_2e) emissions for pellet systems as compared to the geologic CO_2e emissions from an oil heating system, and limited biogenic carbon emissions associated with pellet manufacturing.

Methods

The use case for the analysis is a hypothetical 2,000 square foot (SF) single-family, newly constructed home in the center of Montpelier, VT. It is a central location in Vermont and does not favor transportation coming from any one direction. The home is representative of a new Vermont home with a heating load of 50 MMBtu or 52,750 MJ per year, which is an average value for residential new construction.

It is assumed that the boilers will be in use for 20 years, which aligns with the 2019 R&D GHG Taskforce requirements. Using the Intergovernmental Panel on Climate Change's recommended 100-year time frame for lifecycle GHG emissions, the taskforce decided to report on **kg of CO_2e / MJ of fuel** for fuel associated emissions and **metric tons of CO_2e** over a 20-year lifetime of the boilers for the full LCA – all reported values will be bolded for ease of identification.

A product lifecycle has six phases: material sourcing, material processing, product manufacturing, distribution, use and end of life. Both boiler types and their respective fuels were analyzed in each of these phases. Using available product information, the following lifecycle phases were considered for this analysis: boiler primary material production emissions, emissions from boiler distribution, fuel

[16] Biology Dictionary, https://biologydictionary.net/carbon-cycle/, retrieved February 24, 2020.

extraction and processing emissions, fuel distribution emissions, boiler use (i.e., combustion) emissions, and boiler end of life disposal emissions. Complete data was not available for each phase considered in this analysis and clarifications are provided regarding key assumptions and any omissions due to incomplete data.

Fuel storage system lifecycle analysis, black carbon emissions throughout the entire lifecycle[17], and fluctuations in forest soil carbon are not included in the scope of this project.

Results

Fuel Oil Boiler

A high-efficiency oil boiler was selected from a large retailer's website, as shown in Figure 12, to match the analysis home's heating load. The Slant/Fin Liberty II[18], model LD-30, capable of 154,000-175,000 Btu per hour, is representative of a common boiler selected for new homes in Vermont and had equipment information available online for the purpose of this analysis.

Figure 12: Slant/fin Liberty II oil boiler[19]

Boiler Primary Material Production

Manufacturer specifications indicated that most of the boiler, weighing in at 448 lbs., is made of steel and/or cast iron. Slant/Fin was not able to provide detailed information beyond the online product composition information. Based on the online documentation and the information collected about the AWH boiler, the authors assumed that the oil boiler was 90 percent steel and 10 percent insulation, plastics and other materials by weight. An environmental product declaration was not found for either boiler. Given the lack of specific information on the material composition of the boiler, the authors calculated the boiler's embodied carbon from manufacturing as if the boiler was made of 90% steel. The other 10% of materials is excluded from the calculation.

[17] Black carbon is made up of the soot and other fine particulate matter emitted when diesel, coal, and biomass fuels are burned.
[18] Slant/Fin Liberty II product information: https://www.slantfin.com/library/liberty-ii/
[19] Direct Brand. Slant/Fin Liberty LD-30PT Hot Water Boiler. https://www.direct-brand.com/oil-systems/sf-ld-30-pt-of-hw-blr-pk-w-tls-sf/?utm_source=Google%20Shopping&utm_campaign=KH-Google%20Shopping%20Feed&utm_medium=cpc&utm_term=31647&gclid=CjwKCAiAs92MBhAXEiwAXTi257XEqr_cX6GlAm6mblv1HV2ZeMSpbO3KyClfjtOQl8iBd4ZvIyo_gxoCnPsQAvD_BwE

Steel and iron are carbon intensive products, responsible for anywhere from 4% to 7% of global GHG emissions.[20] For every metric ton of steel produced, 1.85 metric tons of CO_2e are emitted, or 0.84 kg CO_2e per pound of steel. [21]

Knowing that the remaining 10% of the boiler, including insulation, plastics, gauges, and other materials, has embodied carbon that is not accounted for, this analysis likely under-estimates the embodied GHG emissions of the oil boiler. **The total embodied emissions for the oil boiler unit is 338 kg of CO_2e.**

Boiler Distribution

Both boilers have products that are made all over the world, and it was not possible to incorporate the embodied carbon of each piece of the boiler being transported to the U.S. Therefore, this analysis starts with the embodied carbon of steel boiler at the assembly point. The Slant/Fin oil boilers are assembled and shipped from Slant/Fin Corp. in Greenvale, NY, directly to a local supplier in Montpelier, VT, a distance of 316 miles. The average freight truck in the U.S. emits 161.8 grams of CO_2 per ton-mile.[22] A ton-mile is the equivalent of shipping one ton of product one mile. According to Slant/Fin, each truck from Greenvale may carry as many as 60 units to a local supplier. Assuming the truck has additional stops adding 25% to the direct route, **this leg contributes 12.8kg of CO_2e to the embodied carbon of each boiler**.

The final trip for the boiler, from the supplier to home, is assumed to be a 10-mile round trip. For a delivery of single unit, a Ford Transit-350 was the assumed vehicle. With a combined fuel economy of 16mpg, **this trip adds 5.5 kg of CO_2e to the delivery of one boiler.**[23]

Boiler Use

The oil boiler is installed and used for 20 years, serving the home heating load of 50 mmBtu per year. With a boiler efficiency of 86%, the home will be using 58 mmBtu or 61,340 MJ per year, or 423 gallons of oil each year[24]. Over the 20-year life of the boiler, the home consumes a total of 8,464 gal of fuel.

Calculations for the emissions associated with the extraction, processing, distribution, and burning of this fuel oil are included in the next section.

Fuel Extraction & Processing

To accurately compare the two boilers' emissions, emissions associated with each boiler's fuel lifecycle must be considered. This section assesses emissions associated with crude oil extraction and processing up to the point of the refinery gate.

For a conservative estimate of the associated emissions from shipment, the heating oil is assumed to be acquired and refined in the U.S., rather than overseas. This is highly likely in today's energy market

[20] European Commission, "Energy Efficiency and CO_2 Reduction in the iron and Steel Industry," https://setis.ec.europa.eu/system/files/Technology_Information_Sheet_Energy_Efficiency_and_CO2_Reduction_in_the_Iron_and_Steel_Industry.pdf

[21] World Steel Association, "Steel's Contribution to a Low Carbon Future," retrieved February 26, 2020, https://www.worldsteel.org/publications/position-papers/steel-s-contribution-to-a-low-carbon-future.html

[22] Mathers, J., 2015. "Green Freight Math: How to Calculate Emissions for a Truck Move," EDF + Business, https://business.edf.org/insights/green-freight-math-how-to-calculate-emissions-for-a-truck-move/

[23] AutoBlog, "2019 Ford Transit-350." https://www.autoblog.com/buy/2019-Ford-Transit_350/?guccounter=1

[24] U.S. Energy Information Administration. "Units and calculators explained," https://www.eia.gov/energyexplained/units-and-calculators/

conditions; about 89% of U.S. petroleum consumption currently comes from domestic sources.[25] Of the domestic sources, Eagle Ford produces the most barrels per day and is assumed to be the source of fuel oil in this analysis.[26]

While steps in the domestic heating oil supply chain were difficult to identify, the oil industry commonly quantifies their GHG impacts. The oil industry uses standard reporting mechanisms, and one such reporting metric is well-to-refinery gate (WTR).[27]

This scope includes crude oil pumped from the ground in Eagle Ford, Texas, then piped from Eagle Ford to the refinery gate in Corpus Christi, Texas. According to Table 44 of the Eagle Ford Shale Oil Report, captured in Figure 13, diesel, a reasonable proxy for oil, has a **WTR emissions of 5.0 g CO_2e / MJ.**[28]

TABLE 44 WTW GHG emissions, in g CO_2e/MJ, of gasoline, diesel, and jet fuels derived from crude oil produced in the BO and VO zones in the Eagle Ford play

	WTR[a]	WTP[b]	PTW[c]	WTW
Gasoline Blendstock	4.3	16.0	73.2	89.2
Diesel	5.0	12.2	75.6	87.8
Jet	5.1	9.6	72.9	82.5

[a] Well-to-refinery gate
[b] Well-to-pump
[c] Pump-to-wheels

Figure 13: Table 44 of the Eagle Ford shale oil report[29]

At the refinery in Corpus Christi, the crude oil is processed into a variety of petroleum derivatives. The emissions associated with **processing crude oil into diesel, again, the proxy for heating oil, adds another 4.9 g CO_2e / MJ of oil.**[30]

[25] U.S. EIA, 2019., "Frequently Asked Questions: How much oil consumed by the United States comes from foreign countries?" https://www.eia.gov/tools/faqs/faq.php?id=32&t=6
[26] U.S. EIA, Feb 18, 2020. "Petroleum & Other Liquids: Drilling Productivity Report," https://www.eia.gov/petroleum/drilling/#tabs-summary-1
[27] Argonne National Laboratory, "Well to Wheels," retrieved December 23, 2019, https://greet.es.anl.gov/greet/gettingstarted/wtw.html
[28] Institute of Transportation Studies, University of California Davis, 2019. "Energy Intensity and Greenhouse Gas Emissions from Crude Oil Production in the Eagle Ford Region: Input Data and Analysis Methods," https://vine.veic.org/evt/ets/PublicDocuments/Research%20and%20Development/2019%20R%2BD/GHG/Reference%20Materials/EagleFord_Shale_Oil_Report.pdf?Web=1
[29] Institute of Transportation Studies, "Energy Intensity and Greenhouse Gas Emissions from Crude Oil Production in the Eagle Ford Region: Input Data and Analysis Methods."
[30] Elgowainy, A., J. Han, H. Cai, M. Wang, G. S. Forman and V. B. DiVita (2014). Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S. Refineries. Environmental Science & Technology 48(13): 7612–7624.

Fuel Distribution

From the refinery gate in Corpus Christi, the oil is shipped to the Northeastern US. For this analysis, it is assumed that the Port of Albany, NY, is the receiving port - a distance of 2,444 nautical miles[31] via an AFRAMAX vessel with a payload of 120,000 dead weight tons.[32] Application of emission factors from the EPA's Emission Factors for Greenhouse Gas Inventories of 0.0408 CO_2e per ton-mile[33] to the 293,280,000 total ton-miles necessary in this trip results in another **0.0026 kg of CO_2e of emissions per MJ of fuel delivered**.

Once in Albany, NY, the fuel oil is offloaded onto a tanker truck with an 8,000-gallon capacity, and the same fuel economy as the freight truck delivering boilers, 161.8 g CO_2e per ton-mile. This truck travels directly to a Montpelier, VT, supplier, 159 miles away, adding **0.00072 kg of CO_2e to each MJ of fuel delivered**.

From the supplier in Montpelier, VT, the oil is delivered to the home via a smaller straight back fuel truck. A typical fuel truck carrying about 3,000 gallons of fuel is assumed to have a fuel economy of 7 miles per gallon[34]. Like the delivery of the boiler to the home, the total miles assigned to the final leg of travel from supplier to end user is 10 miles, where 200 gallons of oil are delivered. This trip adds **0.000034 kg of CO_2e to each MJ of fuel.**

Combustion

The EPA's 2020 greenhouse gas inventory was used to calculate the CO_2e emissions of oil combustion.[35] In addition to the direct CO_2 emissions, CH_4 and N_2O are also included at a higher global warming potential of 25 and 298, respectively. **The total CO_2e emissions associated with combustion are 0.0703 kg of CO_2e for each MJ of fuel.**

Boiler End of Life

Rather than accounting for end-of life disposal, it is expected that the boiler materials will be recycled. While there are emissions from recycling there are also avoided carbon emissions from using recycled materials (versus sourcing virgin materials). No avoided **CO_2e** emissions are assigned to this step of the lifecycle because the avoided emissions of using recycled steel would be claimed by the manufacturer of whatever product is made from the recycled steel.

Advanced Wood Heating Pellet Boiler

The OkoFEN Pellematic® PE(S) 48 kW pellet boiler[36] selected for the analysis is the most common pellet boiler for a Vermont installation and meets the heating load for the analysis home. The Pellematic is an automatic pellet boiler that burns wood pellets to heat water, just as the oil boiler analyzed above. Hot water is then circulated throughout the home distributing heat hydronically.

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[31] Ports.com. "Sea route & distance: Port of Corpus Christi to Port of Albany-Rensselaer". http://ports.com/sea-route/#/?a=1812&b=1686&c=Port%20of%20Corpus%20Christi,%20United%20States&d=Port%20of%20Albany-Rensselaer,%20United%20States

[32] U.S. Energy Information Agency, 2014. "Oil tanker sizes range from general purpose to ultra-large crude carriers on AFRA scale." https://www.eia.gov/todayinenergy/detail.php?id=17991

[33] U.S. EPA, 2020. "Emission Factors for Greenhouse Gas Inventories" Table 8. https://www.epa.gov/sites/default/files/2020-04/documents/ghg-emission-factors-hub.pdf

[34] Heavy Duty Trucking (HDT). The Fleet Business Authority. 2020 Fact Book. Sustainability - SmartWay Fleet Fuel Mileage. Pg 43. August 2020. http://digital.truckinginfo.com/August2020?m=65490&i=684501&p=2&uri=%2FAugust2020&ver=html5

[35] U.S. EPA, 2020. "Emission Factors for Greenhouse Gas Inventories" Table 1. https://www.epa.gov/sites/default/files/2020-04/documents/ghg-emission-factors-hub.pdf

[36] OkoFEN Pellematic product information: https://www.oekofen.com/en-gb/pellematic/

Although OkoFEN is headquartered in Austria, the pellet boilers sold in the U.S. are assembled in Bethel, Maine, by Maine Energy Systems. Both boilers have parts that are produced all over the world, and within this scope of work, it was not possible to incorporate the LCA of each piece of the boiler being transported to the U.S. Therefore, this analysis omits the embodied carbon of the 10% of the boiler that is not steel and begins with the embodied carbon of the steel boiler at the point of assembly.

Boiler Primary Material Production

By weight, the Pellematic is made mostly of steel (90 percent), and also contains some refractory brick, insulation, and plastic, according to Maine Energy Systems. The unit weighs in at 605 kg or 1,334 lbs.[37] As previously stated, for every metric ton of steel produced, there are 2 tons of CO_2e emitted, and no environmental product declaration was available for either boiler. Based on a conversation with the manufacturer about the Pellematic boiler composition[38], the makeup is generally the same as the oil boiler. **Therefore, the total embodied CO_2e of the steel for the Pellematic unit is 1007.3 kg CO_2e of steel.**

Boiler Distribution

The assembled Pellematic unit is shipped on an average freight truck[39] from Bethel, ME, to the supplier in Montpelier, VT, a distance of 118 miles. It is assumed that the truck is carrying three Pellematics to be delivered directly to the supplier in Montpelier, VT, equating to 4,000 lbs of cargo, or 2 imperial tons, and that another Ford Transit-350[40] delivers the unit from the supplier to the analysis home carrying one Pellematic. Together, these two trips **add 19.7 kg CO_2e to the LCA of the pellet boiler.**

Boiler Use

Following installation, the boiler is ready to be used for the planned 20-year lifespan. As mentioned previously, the home heating value is 50mmBtu per year. The Pellematic boiler has a slightly lower efficiency than the Liberty II oil boiler. At 84% efficiency, the home consumes 60 mmBtu or 62,801 MJ per year, and with an energy density of 16.6mmBtu/ton, each year, the home will burn 3.59 tons of pellets and 71.72 tons of pellets over 20 years.

Fuel Extraction & Processing

Wood is the most local source of heating fuel available on the Vermont market. There is currently only one pellet mill in Vermont and a numerous mills within driving distance of Vermont. The Vermont Wood Pellet mill located in North Clarendon, VT, was used for this analysis. Vermont Wood Pellet serves many Vermont customers, especially in central Vermont. The mill sources its feedstock wood within a 30-mile radius because of the abundance of available pine pulpwood regularly harvested from surrounding managed private forests. Sourcing wood fiber from distances greater than 30 miles is not cost effective for Vermont Wood Pellet. The mill sources logs that need to be debarked, chipped, dried, reground, and extruded into a pellet form.[41] Regionally, there are some pellet mills that use pre-pulverized, pre-dried sawdust residue to make pellets, and it is important to note that such pellets have even fewer embodied carbon emissions.

For this analysis, it was assumed that the Vermont-made pellets were sourced from Vermont roundwood – harvested from Eastern White Pine stand on privately owned, managed forestland on the

[37] OkoFEN Pellematic Technical data: https://www.oekofen.com/assets/download/Englisch/Pelletskessel/Technische%20Daten/TD_Pellematic_en_aktuell.pdf
[38] Maine Energy Systems Interview with BJ Otten by Lauren Morlino, December 16, 2019.
[39] Mathers, J., 2015. "Green Freight Math: How to Calculate Emissions for a Truck Move."
[40] AutoBlog, "2019 Ford Transit-350."
[41] Vermont Wood Pellet Interview of Chris Brooks by Lauren Morlino, December 27, 2019.

outer edge of the 30-mile radius in which Vermont Wood Pellet operates. **When emissions from harvesting and processing are summed, they contribute 0.00784 kg CO_2e/MJ of pellets.**[42]

Fuel Distribution

For this analysis, haul distance from the pellet mill directly to consumer is assumed to be less than 100 miles. **Emissions associated with delivery results in an additional 0.00294 kg CO_2e/MJ of pellets delivered.**[43]

Combustion

Like the fuel oil analysis, the EPA's greenhouse gas inventory list was applied to sum the weighted GWPs of CO_2, CH_4 and N_2O. However, unlike the fuel oil analysis, only the non-biogenic CO_2e emissions associated with direct combustion of the pellets were included in the final CO_2e count, and it is assumed that 90% of the pellet's CO2 emissions are carbon neutral. Vermont's forests are well managed and forest landcover rates have been steady over several decades. Vermont currently harvests far less wood than is grown each year. Yet, inevitably a small portion of wood may be sourced from non-forest management activities such as land-clearing for agriculture or development. To be conservative in our approach and account for the potential of a small portion of wood sourced from non-sustainable activity, we assumed that 10% of the wood sourced from the pellet mill would not be fully recouped within a 100-year lifecycle.[44] Accordingly, CH_4 and N_2O GHG emissions from wood combustion contributes 0.00119 kg CO_2e /MJ, while 10% of the of the total biogenic CO_2 emissions adds another 0.00888 kg CO_2e /MJ.[45] All told, pellet combustion emits **a total of 0.01007 kg of CO_2e / MJ of pellets**.

Boiler End of Life

Just as with the oil boiler, rather than accounting for end-of life disposal, it is expected that the boiler materials will be recycled. While there are emissions from recycling there are also avoided carbon emissions from using recycled materials (versus sourcing virgin materials). No avoided **CO_2e** emissions are assigned to this step of the lifecycle because the avoided emissions of using recycled steel would be claimed by the manufacturer of whatever product is made from the recycled steel.

Summary of Results

In the following section, results listed above are assembled to provide a summary of CO_2e emissions associated with the equipment, the fuel production and transportation, the operation of each boiler, and finally, a summed total of the CO_2e emissions over of the entire lifetime of the fuel oil boiler and the pellet boiler systems.

Fuel Oil Boiler

Boiler Primary Material Production and Distribution

The embodied carbon of the steel within the boiler and the transportation of the boiler from manufacturer to home results in a total of 357 kg CO_2e for each boiler, as seen in Table 3.

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[42] Unnasch. S. and L. Buchan (2021). Life Cycle Analysis of Renewable Fuel Standard Implementation for Thermal Pathways for Wood Pellets and Chips, Life Cycle Associates Report LCA.6161. 209.2021, Prepared for Technology Transition Corporation.

[43] Unnasch and Buchan, Life Cycle Analysis of Renewable Fuel Standard Implementation for Thermal Pathways for Wood Pellets and Chips.

[44] Biomass Energy Resource Center, 2016. "Summary of Carbon Emission Impacts of Modern Wood Heating in Northeastern US," https://gmcboard.vermont.gov/sites/gmcb/files/files/certificate-need/veic-carbon-emission-and-modern-wood-heating-summary.pdf

[45] U.S. EPA, 2020. "Emission Factors for Greenhouse Gas Inventories" Table 1.

Table 3. Fuel oil boiler equipment embodied and upstream emissions (kg CO_2e)

Fuel Oil Boiler – LCA Stage	kg CO_2e emitted
Embodied Emissions in Steel	338
Assembly to Supplier	13
Supplier to Home	6
Total	357

Boiler Use – Fuel Extraction, Processing, Distribution, & Combustion

Upstream emissions from oil includes WTR emissions, transport from refinery gate to regional port, from port to local supplier, from supplier to home. In sum, these steps add 0.0084 kg CO2e/MJ of fuel oil. The addition of combustion emissions increases the value, nearly ten-fold, to 0.0787 kg CO2e/MJ of fuel oil, as seen in Table 4.

Table 4. Upstream emissions of fuel oil extraction, processing, transportation, delivery, and combustion (kg CO_2e / MJ of fuel oil).

Fuel Oil Extraction, Processing, and Distribution – LCA Step	kg CO2e/MJ of Fuel Oil emitted
Well-to-Refinery	0.00500
Refinery	0.00490
Refinery to Port - Tanker Ship	0.00262
Port to Supplier - Class 8 Tanker Truck	0.00072
Supplier to Home - Class 7 Tanker Truck	0.00003
Fuel Oil Combustion	0.07030
Total	0.08362

Boiler Lifetime Emissions

Over the 20-year lifetime of the boiler and the 8,460 gallons of fuel oil consumed, the total emissions from this heating system is 96.9 metric tons of CO_2e. A breakdown accounting for emissions of each step is found below in Table 5.

Table 5. Lifetime emissions of fuel oil boiler over 20-years of use (metric tons).

Fuel Oil Boiler – LCA Stage	Metric Tons CO_2e emitted
Boiler Manufacturing & Delivery	0.4
Fuel Extraction/Refining	12.1
Fuel Transport & Delivery	4.1
End Use Combustion	86.3
Total	102.9

Advanced Wood Heating Pellet Boiler

Boiler Primary Material Production and Distribution

The carbon footprint of the boiler itself is determined by the embodied carbon of the steel, transportation from assembly to supplier and supplier to home. The total, found in Table 6, is for each pellet boiler.

Table 6. Pellet boiler equipment embodied and upstream emissions (kg CO_2e)

Pellet Boiler – LCA Stage	kg CO_2e emitted
Embodied Emissions in Steel	1,007
Assembly to Supplier	14.2
Supplier to Home	5.5
Total	1,027.0

Boiler Use – Fuel Extraction, Processing, Distribution, & Combustion

The individual steps and GHG emission values of pellet making process, delivery and combustion are found in Table 7. Timber harvesting to bulk pellet fuel distribution to consumer, are pulled from Unnasch and Buchan., while final combustion uses methodology from BERC 2016 and values from the EPA GHG Inventory list.[46, 47,48]

Table 7. Upstream emissions of pellet extraction, processing, transportation, delivery, and combustion (kg CO_2e / MJ of pellets).

Pellet Boiler – LCA Stage	kg CO_2e/MJ emitted
Harvesting & forwarding	0.00227
Transport from landing to mill	0.00140
Mill operations	-
Debarking	-
Grinding	0.00038
Drying	0.00129
Regrinding and Extrusion	0.00250
Bulk distribution to consumer	0.00294
Combustion (accounts for CH_4, N_2O and 10% of biogenic carbon)	0.01007
Total	0.02085

Boiler Lifetime Emissions

Over the 20-year lifetime of the pellet boiler and the 3.59 tons of pellets consumed, the total emissions of the system is 27.2 metric tons of CO_2e (Table 8).

Table 8. Lifetime emissions of pellet boiler over 20-years of use (metric tons).

Pellet Boiler – LCA Stage	Metric Tons CO_2e emitted
Boiler Manufacturing & Delivery	1.0
Fuel Extraction/Processing	8.1
Fuel Transport & Delivery	5.5
End Use Combustion	12.6
Total	27.2

[46] Unnasch and Buchan, Life Cycle Analysis of Renewable Fuel Standard Implementation for Thermal Pathways for Wood Pellets and Chips.
[47] Biomass Energy Resource Center, 2016. "Summary of Carbon Emission Impacts of Modern Wood Heating in Northeastern US."
[48] U.S. EPA, 2020. "Emission Factors for Greenhouse Gas Inventories" Table 1.

Discussion

Lifetime CO_2e emissions of the pellet system, at 27.2 metric tons, are 74% less than those of the fuel oil system, at 102.9 metric tons. However, only a difference of 2 metric tons is found in the embodied carbon of the equipment, and upstream emissions associated with fuel extraction, processing, transportation, and distribution as shown in Figure 14. The majority of the savings are determined by the carbon intensity of the direct emissions of combustion during end use heating the home. In fact, oil combustion over the 20-year lifetime of the boiler emits 86.3 metric tons of CO_2e, while the pellet system releases 85% less, just 12.6 metric tons of CO_2e emissions.

Discounting the biogenic CO_2 emissions from pellet combustion heavily tips the scales in favor of pellet heating systems. While distinguishing between biogenic and geologic sources of carbon emissions in the methodology drastically influences the results, this approach is validated by both evidence that Vermont's forests are well managed and continue to sequester additional carbon each year,[49] and by the scientific and energy policy communities around the world that widely recognize this fundamental distinction. For example, numerous reports issued by the IPCC have recognized the importance of sustainable forest management and the use of wood fuels as a key strategy for long-term carbon emission mitigation.[50] In addition, the carbon intensity of pellets calculated in this analysis is within the range of the IPCC's lifecycle GHG emissions of North American forestry supported biomass heating.[51]

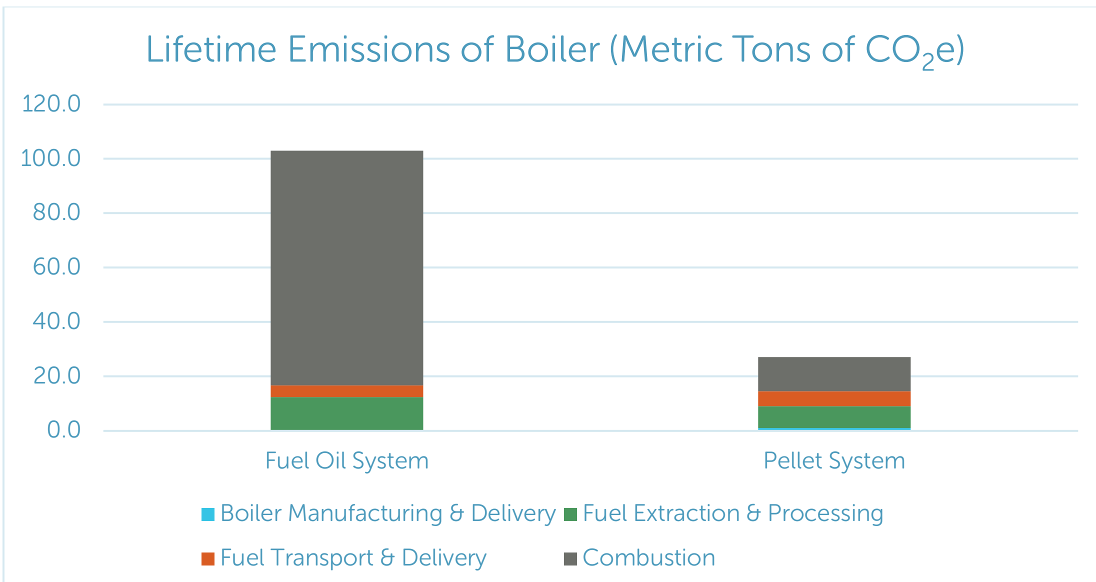

Figure 14. Lifetime emissions of fuel oil and pellet boilers in metric tons of CO_2e.

Future Refinements for this Analysis

Despite many hours of meticulous calculations, interviews, and research, the data is imperfect. The emissions associated with each stage represents estimates of GHG emissions for the assumed paths of

[49] Biomass Energy Resource Center. 2019. Vermont Wood Fuel Supply Study. Prepared for Vermont Department of Forests, Parks and Recreation. 2018 VWFSS Final Report with Letter.pdf (vermont.gov)
[50] https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg3-chapter9-1.pdf
[51] Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C. W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello, 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

equipment and fuels. While plausible paths and reasonable assumptions, the exact supply chain, which is subject to change, will determine the actual emissions associated with each stage.

Additionally, the emissions associated with manufacturing of boiler components and their transportation to the point of assembly were not included in this analysis. If environmental product declarations become available for each boiler or even the fuel, assumptions may be refined for a more accurate comparison of carbon impacts.

Finally, sources of GHG emissions that are not be adequately addressed in this paper include black carbon emissions throughout the entire life cycle and fluxes in forest soil carbon.

Conclusion

This analysis, factoring both its strengths and weaknesses in the data and methods, provides a helpful comparison of the estimated amounts of carbon emitted over the life cycle of an oil boiler system and a pellet boiler system. The results suggest significantly lower lifetime carbon emissions from a pellet boiler system and supports the State of Vermont's policies that incentivize local wood heating as a strategy to reduce the amount of fossil fuels used in Vermont and to mitigate GHG emissions.

Further, the savings are found exclusively in the difference in combustion emissions, and the carbon intensities of the equipment, the fuel extraction and processing, and the fuel transport and delivery are surprisingly similar and may prove inconsequential in the larger comparison.

Additional research is needed to fully account for the embodied carbon emissions associated with the non-steel components and the black carbon emissions of the two boiler systems, as well as the forest soil carbon associated with pellet production.

Appendix 4: Construction Materials

Author: Brian Just

Introduction

The manufacturing of materials for buildings construction represents 11% of global carbon emissions.[52] Embodied carbon of a building – the emissions that result from the extraction, manufacturing and transportation of building materials - can equate to decades of building operation emissions. Thoughtful design and materials selection can result in buildings that greatly reduce – or even store – carbon.

Through greenhouse gas research and development, Efficiency Vermont is exploring the opportunity to further reduce carbon emissions related to energy efficiency programs. The Construction Materials project begins the investigation into current standards for quantifying product emissions impacts and opportunities for Efficiency Vermont programs to track embodied carbon associated with building materials.

Research Questions

1. What are the greenhouse gas impacts of key residential building materials commonly used in Vermont?
2. If Efficiency Vermont encouraged the use of materials with lower greenhouse gas emissions, what impact might that have on the embodied carbon of Efficiency Vermont-supported projects?

Embodied Carbon in Products

Environmental Product Declarations (EPDs)[53] are useful tools for comparing product choices when considering product lifecycle energy impacts. However, differing scoring criteria are used by each EPD standard development entity. To explore these variances, a sampling of seventeen EPDs across an array of common insulation materials were compared. All EPDs adhered to one or more of three different protocols—International Organization for Standardization (ISO) 14025, ISO 21930, or European Standards (EN) 15804. The majority of EPDs downloaded used multiple standards.[54]

EPDs referencing ISO 14025 generally separated global warming potential (and other) impacts into seven categories:

1. Raw Material Acquisition
2. Packing (of EPS Resin and Insulation)
3. Transportation (Resin to Insulation)
4. Insulation Manufacturing

[52] International Energy Agency for the Global Alliance for Buildings and Construction, 2018. "2018 Global Status Report: Towards a zero-emission, efficient and resilient buildings and construction sector." https://globalabc.org/uploads/media/default/0001/01/f64f6de67d55037cd9984cc29308f3609829797a.pdf

[53] EPDs are independently verified reports that provide information about the life-cycle environmental impacts of products.

[54] It is beyond the scope of this work to compare the protocols referenced. For more information, ArchEcology provides an introductory summary: http://www.archecology.com/2017/04/03/environmental-product-declarations-standards-process/.

5. Distribution
6. Installation and Use
7. End of Life

However, at least one case that referenced ISO 14025 reduced impacts to three categories: production, transport, and end of life.

In this project's limited snapshot of products, EPDs that referenced EN 15804 had categories more tightly defined:

Product Stage	Use Stage	End of Life Stage
A1. Raw Material Supply	B1. Use	C1. De-construction demolition
A2. Transport	B2. Maintenance	C2. Transport
A3. Manufacturing	B3. Repair	C3. Waste processing
A4. Transport from the gate to the site	B4. Replacement	C4. Disposal
A5. Assembly	B5. Refurbishment	Reuse-Recovery-Recycling-potential
	B6. Operational energy use	
	B7. Operational water use	

ISO 21930 was referenced by three of the seventeen EPDs. ISO 21930 used the same A-D categories as EN 15804.

Insulation Product Comparison Challenges

While categories are well defined and provide the appearance of detailed information allowing for clear product comparisons, across the seventeen EPDs evaluated, it was common for most of the A-D subcategories to list module not declared (MND) in place of data. For example, the EPD for Gutex wood fiber insulation reports only A1, A2, A3, C3, and D. Steico, another wood fiber insulation, reports the same subcategories but adds C2.

Even with products providing the same categories, there is not consistency with functional units in those categories. For example, here are three products that reference EN 15804 and the reported functional unit for the product:

1. Gutex fiberboard: 1 m^3
2. CAPEM cellulose: 1 kg
3. Dow Xenergy extruded polystyrene: 0.1 m^3

Unfortunately, this means that even when there is consistency in reporting the lifecycle stages (e.g. A1-A3 being listed), conversions are necessary. And, geography matters: A European EPD is not necessarily valid as representative of a product class with North American-made alternatives.

Within the subset of seventeen EPDs, reporting was given using a building service life of 50-year, 60-year, 75-year, or 100-year terms; equating apples to apples with this variability makes things even more difficult, though this is not an issue when looking at cradle-to-gate production (i.e. no operations / use stage considered). As such, cradle to gate production (A1-A3) is used for all of the example calculations in this report.

Setting aside lifetime basis and geography, and focusing on functional units for the time being, here is one example for calculating a building material's embodied emissions:

> Consider an EPD for a **cellulose** material that indicates the A1-A3 (Raw materials + Transport (Product Stage) + Manufacturing) total to be 0.08 kg CO_2e per kg of material. The cellulose material is installed in one bay of a 2x6 wall cavity that is 8' high (5.5" * 16" * 96") at a density of 3.4 lb/ft^3. The material in the cavity weighs 7.54 kg[55], yielding **0.60 kg** CO_2e (7.54 kg material * 0.08 kg CO_2e / kg material). The cellulose provides R-20 of insulating value in the wall cavity.
>
> Fill the same wall cavity with **extruded polystyrene (XPS)**. A relevant EPD gives an A1-A3 total to be 10.2 kg CO_2e per 0.1 m^3 of material. The 5.5" * 16" * 96" wall cavity equates to 0.138 m^3, yielding 14.1 kg CO_2e for the cavity.[56] But at R-5 per inch, this XPS equates to R-27.5 and the CO_2e must be scaled back to an R-20 basis. This yields **10.3 kg** CO_2e for R-20 equivalent (14.1 kg CO_2e * 20/27.5).
>
> Now for **fiberglass**. An EPD for a recycled content fiberglass batt shows an A1-A3 total of 0.61 kg CO_2e per 1 m^2 at RSI-1. (RSI is the R-value in international (SI) units.) The area of the 16" x 96" cavity is 0.99 m^2 (16" * 96" * 0.000645 m^2/"). This yields 0.604 kg CO_2e at RSI-1 (0.61 kg CO_2e / m^2 * 0.99 m^2), or R-5.68 of material thickness in imperial units. Scaling to R-20, the value is **2.13 kg** CO_2e (0.604 kg CO_2e * 20/5.68).

Clearly, comparing EPDs is not as straightforward as might be hoped.

Insulation Product Comparison

Despite obstacles, the team compared several insulation materials on like terms. The products included:

- 3 fiberglass batts
- 3 cellulose
- 2 extruded polystyrene (XPS)
- 2 expanded polystyrene (EPS)
- 2 polyisocyanurate (1 product excluded; EPD didn't clearly distinguish system boundary)
- 2 fiberboard
- 1 phenolic foam

The EPDs used were either manufacturer-reported or manufacturer-agnostic as reported by a third party such as the Cycle Assessment Procedure for Eco-Materials (CAPEM).

Analysis and assumptions were completed in a spreadsheet. All values were converted on the basis of a function unit of R-20 thickness worth of material applied to a 100 ft^2 area; this can be updated to whatever functional unit proves most convenient later on. Averaged results by product type for global warming potential (GWP) in kg CO_2e are provided in Table 21.

Table 9. Average GWP per insulation product type

Material	Avg, kg CO2e per 100 ft^2 at R-20	Notes

[55] ((5.5" * 16" * 96") / (1728"/ft^3)) * 3.4 lb/ft^3 * 0.4536 kg/lb. = 7.54 kg
[56] ((5.5" * 16" * 96") / (1728"/ft^3)) * 0.0283 m^3"/ft^3 * (10.2 kg CO2e / 0.1 m^3) = 14.1 kg CO_2e

Fiberboard	-259.7	2 EPDs averaged
Cellulose, dense pack	-88.6	3 EPDs averaged
Fiberglass, batt	23.2	3 EPDs averaged
Phenolic, board	58.2	1 EPD
EPS, board	71.3	2 EPDs averaged
Polyisocyanurate, board	78.7	1 EPD, 1 omitted (suspected outlier); needs investigation
XPS, board	90.2	2 EPDs averaged, 1 omitted (outlier); needs investigation

The cellulose and fiberboard EPDs claimed credit for the stored carbon in the end product. For example, Gutex's EPD states 271.1 kg CO_2e stored in the wood of the soft fiber board, presumably per m^3 functional unit and 173 kg/m^3 density. This is 1.57 kg CO_2e of credit per kg of fiberboard. Steico's EPD says that 65 kg of carbon is bound in the product, corresponding to 239 kg CO^2. At the Steico EPD listed 157.49 kg/m^3 for the functional unit, this is 1.52 kg CO_2e credit per kg of fiberboard.

One XPS product had a GWP nearly an order of magnitude higher than other examples for the product type; this was excluded from the averages in the table above. Similarly, one polyisocyanurate product had a GWP more than double another; this was also excluded.

Note that this was a rough analysis to estimate impacts. Further investigation is needed if Efficiency Vermont were to formally assign factors to these product types for a program. Not all common insulation materials (e.g. mineral wool) nor "low carbon" materials (e.g. straw, hempcrete) were evaluated at this time.

Concrete options comparison

Global CO_2 emissions related to concrete production are significant. The production of one component, cement, dominates the GWP of producing concrete.[57] Substituting a portion of the cement (using supplementary cementitious materials (SCMs)) in a concrete mixture creates an opportunity to reduce GWP impacts.

SCMs include pozzolans that react with calcium hydroxide to form compounds that have cementitious properties.[58] Fly ash, a byproduct of coal combustion, is commonly used to replace from 15% to greater than 50% of the cement portion of concrete mix. High SCM content can have adverse effects such as longer set times that can delay construction. Cold climates add complexity: fly ash concrete is less resistant to scaling and may have pouring temperature limitations. However, even in Vermont's climate it is possible to formulate concrete mixtures containing SCMs that work well for a given application.

[57] Hanle, L., Jayaraman, K., and Smith, J. CO_2 Emissions Profile of the U.S. Cement Industry. https://www3.epa.gov/ttnchie1/conference/ei13/ghg/hanle.pdf

[58] Thomas, M. 2007. Optimizing the Use of Fly Ash in Concrete, Portland Cement Association https://www.cement.org/docs/default-source/fc_concrete_technology/is548-optimizing-the-use-of-fly-ash-concrete.pdf

For the purposes of this work, an estimate of 150 kg CO_2e per tonne (1000 kg) of concrete was used.[59] Fly ash and Pozzotive[60], a post-consumer recycled glass SCM, were briefly analyzed as captured in Example 2 under Potential Impact on Programs below.

Potential Impact on Programs

The project team built a query to analyze project data (via Efficiency Vermont's Mobile App Home Data Form and REM/Rate) for the first 55 homes completed in the Efficiency Vermont residential new construction (RNC) program in 2019. Insulation volume per application was broken out as follows:

- Above grade wall, cavity
- Above grade wall, continuous
- Roof, cavity
- Roof, continuous
- Floor, cavity
- Floor, continuous
- Rim/band joist, cavity
- Rim/band joist, continuous
- Foundation wall, cavity
- Foundation wall, continuous
- Slab, under
- Slab, perimeter

Concrete was broken down by:

- Foundation wall
- Slab

Example 1: Above grade wall cavity insulation

For the 55 RNC homes referenced above, the average volume of above grade wall cavity insulation per home was 761 ft^3. Combining this with the GHG factors in Table 21, the CO_2e impacts of material substitutions were estimated. Assuming 5.5" cavity depth,

If the average home used fiberglass batts:

$$761\ ft3 * 23.2\ kg\ CO_2e\ /\ (100ft^2 * (5.5/12)ft) = 385\ kg\ CO_2e$$

If the average home used dense-packed cellulose:

$$761\ ft3 * -88.6\ kg\ CO_2e\ /\ (100ft_2 * (5.5/12)ft) = -1471\ kg\ CO_2e$$

Thus, the potential impact of substituting cellulose for fiberglass for the average home would be 1856 kg CO_2e reduction. (385 kg CO_2e – (-1471 kg CO_2e) = 1856 kg CO_2e)

Example 2: Concrete

The average home had 568 ft^3 of concrete in foundation walls (slab on grade homes excluded) and 598 ft^3 of concrete in the slab (assuming 6" thickness, as thickness is not currently recorded in Efficiency Vermont data). Average concrete volume per home was 1166 ft^3. The calculations below assume concrete density of 2,400 kg/m^3.

A ballpark estimate is attained by assuming a 30% reduction in cement via use of an SCM such as fly ash or Pozzotive, equates to 30% less concrete in the project (simplified; not calculating exact reduction in cement nor accounting for CO_2e of SCM itself).

[59] Green Ration Book, Carbon Footprint of Concrete, http://www.greenrationbook.org.uk/resources/footprints-concrete/
[60] Urban Mining Northeast, http://urbanminingne.com/

This 30% substitution yields a 2.38 tonne reduction in concrete (0.30 * 1166 ft^3 * (0.00283 m^3/ft^3 * 2400 kg/m^3 * 1 tonne/1000 kg)); at 150 kg CO_2e /tonne of concrete, the rough calculation nets 357 kg CO_2e savings.

Summary and next steps

These calculations and references can be expanded to form a robust methodology for claiming GHG savings from construction materials substitutions, namely insulation materials and concrete. Currently this is most easily applied to Efficiency Vermont's RNC program, but could be expanded to existing homes, multifamily, and commercial buildings.

The shortlist of recommended actions includes:

- For the RNC team's new field data collection tool (under development; release expected Q2 2020), include the capability to collect:
    1. Insulation type, for each insulation category
    2. Thickness of any non-cavity insulation
    3. Foundation wall thickness, and
    4. Slab thickness.
- Develop a streamlined method for determining insulation and concrete volumes for completed RNC projects using field data collection tool functionality.
- Regularly check for market-ready embodied carbon calculators applicable to Efficiency Vermont.[61]
- For Home Performance with ENERGY STAR, Building Performance, and Multifamily projects, evaluate means to collect estimates of insulation and/or concrete.
- Determine the best unit for common conversion of CO_2e for insulation materials; in this analysis, 100sf of R-20 insulation thickness was used.
- Collect more EPDs to aggregate robust average-values, per material/application, so that savings claims are defensible.
- In tandem with other GHG Taskforce efforts, monetize potential GHG impacts.
- Further evaluate RNC data to determine the most cost-effective insulation assemblies for the purposes of New Product Development or a technical reference model (TRM).

[61] At the time of completing this analysis, the Embodied Carbon in Construction Calculator (EC3) wasn't released. It has some useful information but does not have all of the products Efficiency Vermont needs to assess. Another popular tool, Athena Sustainable Materials Institute's EcoCalculator, is applicable to whole-buildings rather than the comparison of specific materials.

Appendix 5: Study of GHG Emissions from in-Use Natural Refrigerants

Author: Lauren Morlino
Analysis: Ali White

Introduction

The global refrigeration market is rapidly changing, and for good reason; current refrigerants contribute significantly to greenhouse gas emissions, and curtailing their use is considered a high-value mitigation strategy.

Project Drawdown,[62] a nonprofit organization comprising global climate scientists and other researchers, places refrigerant management and switching to alternative refrigerants in the top seven solutions for mitigating climate change, as shown in **Table 10**.

Table 10: Solutions for climate change mitigation[63]

** Gigatons CO2 Equivalent Reduced / Sequestered (2020–2050)*

SOLUTION	SECTOR(S)	SCENARIO 1 *	SCENARIO 2 *
Reduced Food Waste	Food, Agriculture, and Land Use / Land Sinks	87.45	94.56
Health and Education	Health and Education	85.42	85.42
Plant-Rich Diets	Food, Agriculture, and Land Use / Land Sinks	65.01	91.72
Refrigerant Management	Industry / Buildings	57.75	57.75
Tropical Forest Restoration	Land Sinks	54.45	85.14
Onshore Wind Turbines	Electricity	47.21	147.72
Alternative Refrigerants	Industry / Buildings	43.53	50.53

The Intergovernmental Panel on Climate Change (IPCC) has also identified refrigerant management as an essential climate change mitigation strategy for keeping global temperature rise from going above 1.5°C relative to 1990 levels.[64] Optimizing refrigeration systems for energy savings in grocery stores is common practice for these customers and their utility efficiency programs, but targeting non-energy greenhouse gas (GHG) emissions is becoming more important. The federal government has been relaxing refrigerant leakage regulation and minimally enforcing it. The outcome is that when Vermont systems leak, there are not systems in place to accurately account for the resulting efficiency losses and disproportionately large GHG impact. When equipment leaks hydrofluorocarbon (HFC) refrigerants, known as potent *superpollutants,* the global warming impact can be thousands of times that of carbon dioxide (CO_2), pound for pound.

HFC refrigerants are synthetic; alternative "natural" refrigerants comprise substances that can be found in the environment. Natural refrigerants have little to no negative impact on climate or on atmospheric ozone. Some industry markets are ready to adopt natural refrigerants—substances such as

[62] Project Drawdown's name refers to the organization's mission to draw down levels of greenhouse gases in the atmosphere and maintain a steady decline. It is a leading resource for climate solutions. https://www.drawdown.org/.
[63] Project Drawdown, n.d. "Table of Solutions." https://drawdown.org/solutions/table-of-solutions.
[64] IPCC, 2018. *"Global warming of 1.5°C."* https://www.ipcc.ch/sr15/download/#full

hydrocarbon, ammonia, and CO_2. For example, grocery stores typically must report system leakage rates more than other sectors, because of the greater charge size of refrigeration equipment and the amount of refrigeration equipment they use. Therefore, grocery stores are ideal candidates for transitioning to natural refrigerants. This would allow them to remain in compliance with present and anticipated future regulations (future proofing) – while reducing energy bills and significantly reducing carbon footprint.

Grocery stores typically use large refrigeration systems that contain multiple compressors in a row (known as DX rack systems). These cycle on and off to provide constant cooling to the reach-in cases, walk-in coolers, and freezers located throughout the store. These rack systems can use either synthetic or natural refrigerants, depending on system design.

Despite its common association as a greenhouse gas, CO_2 is, in fact, a low-impact natural refrigerant compared to synthetic refrigerants. CO_2 operates at peak efficiency in cold ambient climates, making it a great choice for Vermont grocery stores. City Market in Burlington's South End was the first in the state to install a CO_2 system, and since then, Efficiency Vermont has provided incentives and technical systems to another CO_2 system that was installed and commissioned in 2020. Efficiency Vermont is involved with three more CO_2 installation projects expected to be completed by early 2021.

Because CO_2 requires higher operating pressures than any HFC refrigerant, the refrigeration system as a whole – compressors, evaporators, and piping – needs to be designed differently. For that reason, CO_2 system installations are new-construction opportunities[65]. That is, CO_2 would not work in a retrofit application as a drop-in replacement for a system running on HFCs.

This report compares the GHG impact of a shift from a typical grocery store rack system with a blended HFC baseline to a new CO_2 chiller system that uses glycol to reduce charge size.

Research Question

What GHG savings are associated with a CO_2 system beyond the GHG savings associated with the electrical efficiency savings?

Background and Significance

In 2020, Efficiency Vermont claimed energy savings and the corresponding GHG savings[66] for new CO_2 system installations, but could not claim the GHG savings associated with the refrigerant itself. The energy related GHG savings are derived from the baseline performance of an HFC system. The savings claim does not count the direct GHG savings.[67] A typical Efficiency Vermont Incentive Agreement offered to a customer will mention the amount of energy saved in kilowatt-hours (kWh), the expected payback in years, and the pounds of carbon dioxide equivalent (CO_2e) savings that are associated with the kWh of energy saved by the customer's energy efficiency project. This is very useful information to share with the customer who is focused on energy and cost savings. However, it does not present the full, real-world picture of the GHG impacts from the measure.

[65] The classifications of *new construction* and *retrofits* (of existing buildings and systems) pertain to Vermont's regulated energy efficiency program designs. The classifications are tied to budget categories and create the calculation basis for how ratepayer incentive dollars are budgeted and set, each performance period.
[66] That is, lower GHG emissions from lower electricity consumption.
[67] That is, the reduced GHG emissions associated with the refrigerant the system uses.

In this respect, Efficiency Vermont operates without regard for non-energy GHG impacts when moving from one technology to another due to its regulatory mandate to focus only on energy savings.[68] Yet an opportunity exists to better account for a more accurate, fuller GHG impact from installed efficiency measures and to increase customer awareness regarding total GHG impact of their projects.

This opportunity is especially relevant to grocery store refrigeration systems, where natural refrigerants used in place of HFC refrigerants can have direct GHG savings that dwarf those associated with the energy savings.

Methods

To determine the non-energy GHG savings for this project, the project team calculated the **direct emissions** of a baseline rack system using an HFC baseline and industry standard annual leakage rates, compared to the emissions of a CO_2 chiller system using glycol in a secondary loop that supports cooling in all systems.

The direct emissions from a refrigeration system are those related to the direct release of refrigerant from the system. Measurement of these emissions includes estimates of annual leakage[69] and of refrigerant loss at the end of the equipment life. For simplicity, the project team assumed no lost refrigerant at the end of the life of each type of equipment. The team adapted the following equation to calculate annual direct emissions from the California Air Resources Board (CARB) to state emissions in units of CO_2e.[70] GWP is global warming potential, the measure of energy the emissions of 1 ton of a gas will absorb over a 100-year period, relative to the emissions of 1 ton of CO_2. The higher the number, the greater the warming potential.

Equation 1. Direct annual emissions associated with a refrigeration system

$$\text{Annual direct emissions (pounds of } CO_2e \text{ / year)} = [\text{system charge (pounds)}] * [\text{annual leakage / loss rate (\%)}] * [GWP_{refrigerant}]$$

Calculation

Baseline System

The project team modeled a hypothetical new-construction grocery store of 46,000 square feet as the sample in this study. The team also based the parameters used in this hypothetical baseline system on the EPA profile of an average U.S. grocery store.[71] The EPA found that average grocery store equipment

[68] 2021 is the first year when Efficiency Vermont's performance structure included GHG reduction QPIs for both electric and TEPF efficiency respectively. The new GHG QPIs include both energy and non-energy GHG savings, though the only electric measures included in Efficiency Vermont's 2021-2023 Demand Resources Plan model that have non-zero values for non-energy GHG reductions, include some refrigeration measures such as those related to refrigerant management. There are no TEPF measures in the 2021-2023 model that include non-energy GHG reduction values.

[69] Fricke, Brian A., Vishaldeep Sharma, and Omar Abdelaziz, 2017. "Low Global Warming Potential Refrigerants for Commercial Refrigeration Systems." ORNL / TM-2017 / 289; CRADA / NFE-11-03242. Oak Ridge, TN.: Oak Ridge National Laboratory (ORNL). https://info.ornl.gov/sites/publications/Files/Pub75272.pdf.

[70] Gallagher, Glenn, Bela Deshpande, Pamela Gupta, and Anny Huang, 2016. "California's High Global Warming Potential Gases Emission Inventory: Emissions Inventory Methodology and Technical Support Document," 2015 Ed. Sacramento, CA: California Air Resources Board (CARB). https://ww3.arb.ca.gov/cc/inventory/slcp/doc/hfc_inventory_tsd_20160411.pdf.

[71] U.S. EPA, "Profile of an Average U.S. Supermarket's Greenhouse Gas Impacts from Refrigeration Leaks Compared to Electricity Consumption." Washington, DC: EPA and Advanced Refrigeration Partnership, GreenChill. https://www.epa.gov/sites/production/files/documents/GC%20Average%20Store%20Profile-%20FINAL%20JUNE%202011.pdf.

uses 3,500 pounds of refrigerant and has an annual leak rate of 25 percent of its total charge. For the baseline system refrigerant, the team used the refrigerant 404a, which the EPA cites as the most common in grocery store systems. The GWP of this refrigerant is 3,900.[72]

To calculate the direct annual emissions associated with the baseline system, the team used the equation above with the following baseline inputs:

Equation 2. Direct annual emissions of the baseline system

Annual direct emissions = [3,500 pounds] * [0.25] * [3,900] = **3,412,500 pounds of CO_2e / year**

This calculation aligns with the EPA's calculated annual emissions based on similar inputs.

CO2 System

The inputs for the CO_2 system configuration used in this comparison come from a sample project that Efficiency Vermont worked on at a ~46,000 sf grocery store. Because the modeled case here was a new-construction project, the project team used the baseline calculation for determining the baseline for energy consumption calculations and for direct GHG emissions. The team hypothesized a customer who specified an innovative system for its ability to reduce refrigerant charge as much as possible, a CO_2 primary with a glycol secondary loop. This entailed a packaged CO_2 chiller with a heat exchanger linked to a glycol loop that was circulated out to the cases and walk-ins. In this system configuration, the refrigerant is contained within the packaged chiller, which significantly reduces the amount of refrigerant (charge size) required by the system. Packaged chiller systems are factory sealed and typically have much lower leakage rates than direct-expansion rack systems. Therefore, the charge specified for this system was 400 pounds of CO_2, which has a GWP of 1.[73] CO_2 refrigeration systems operate at high pressures that can build to dangerous levels during a power outage. Because of this, the system has pressure relief valves that "burp," or release refrigerant gas, as necessary. Refrigerant CO_2 is not subject to any leak regulations, so annual leakage rates of 100 percent are not uncommon. Based on the customer's other CO_2 systems' historical data, and to be conservative in its estimates, the project team used a leak rate of 100 percent in Equation 3.

Equation 3. Direct annual emissions of the CO_2 system

Annual Direct Emissions = [400 pounds] * [1] * [1] = **400 pound CO_2e / year**

Obviously, this is a much more straightforward equation than the baseline system equation. In another example, if a case involved a CO_2 rack system with the same charge size as the baseline system, the annual direct emissions would still be only 3,500 pounds of CO_2e / year.

Results

The annual direct GHG emissions savings from a CO_2 system are immense.

Equation 4. Direct annual GHG savings from a CO_2 system

Annual direct emissions savings = [direct annual emissions]$_{baseline}$ - [direct annual emissions]$_{CO_2}$

Therefore, annual direct emissions savings = **3,412,500 pounds of CO_2e / year - 400 pounds of CO_2e / year = <u>3,412,100 pounds of CO_2 / year</u>**.

[72] Refrigerant Management Program, n.d. "High-GWP Refrigerants." Sacramento, CA: CARB. https://ww2.arb.ca.gov/resources/documents/high-gwp-refrigerants.
[73] CARB, 2020, "High-GWP Refrigerants," https://ww2.arb.ca.gov/resources/documents/high-gwp-refrigerants, retrieved October 1, 2020.

Using Vermont's electricity use emission factor, 1.07 pounds of CO_2e per kilowatt hour, a project would have to save 3,188,879 kWh to achieve the same reduction in indirect GHG emissions.

Converted, the refrigerant-based direct emissions reduction is 1,545 metric tons of CO_2e annually, equating to 30,900 metric tons over 20 years.

Meanwhile, the energy savings for this sample project are 700 MWh / year, or 339 metric tons of CO_2e. The energy and refrigerant GHG savings, combined, offer a total of 37,680 metric tons of CO_2e saved across 20 years of the system's operation.

Conclusions

Natural refrigerant solutions are important new technologies for Efficiency Vermont to support. However, market opportunities for such technologies occur only when systems are being replaced or new systems are being built. This analysis demonstrates the significant impact that just one refrigeration system can have.

Efficiency Vermont estimates that there are more than 200 commercial refrigeration rack systems of differing sizes in the state. As systems reach (or exceed) their estimated 20-year equipment lifetimes, Efficiency Vermont has shown that conversations with customers about the benefits of choosing CO_2 for their next system are constructive.

Being able to consistently calculate and capture the direct GHG emissions of these projects is a useful tool, both in customer interactions and impact reporting. But because the majority of real-world GHG savings are not accounted for in regular reporting, Efficiency Vermont and the State may be missing opportunities to claim valuable carbon savings that support the State's energy and climate change goals.