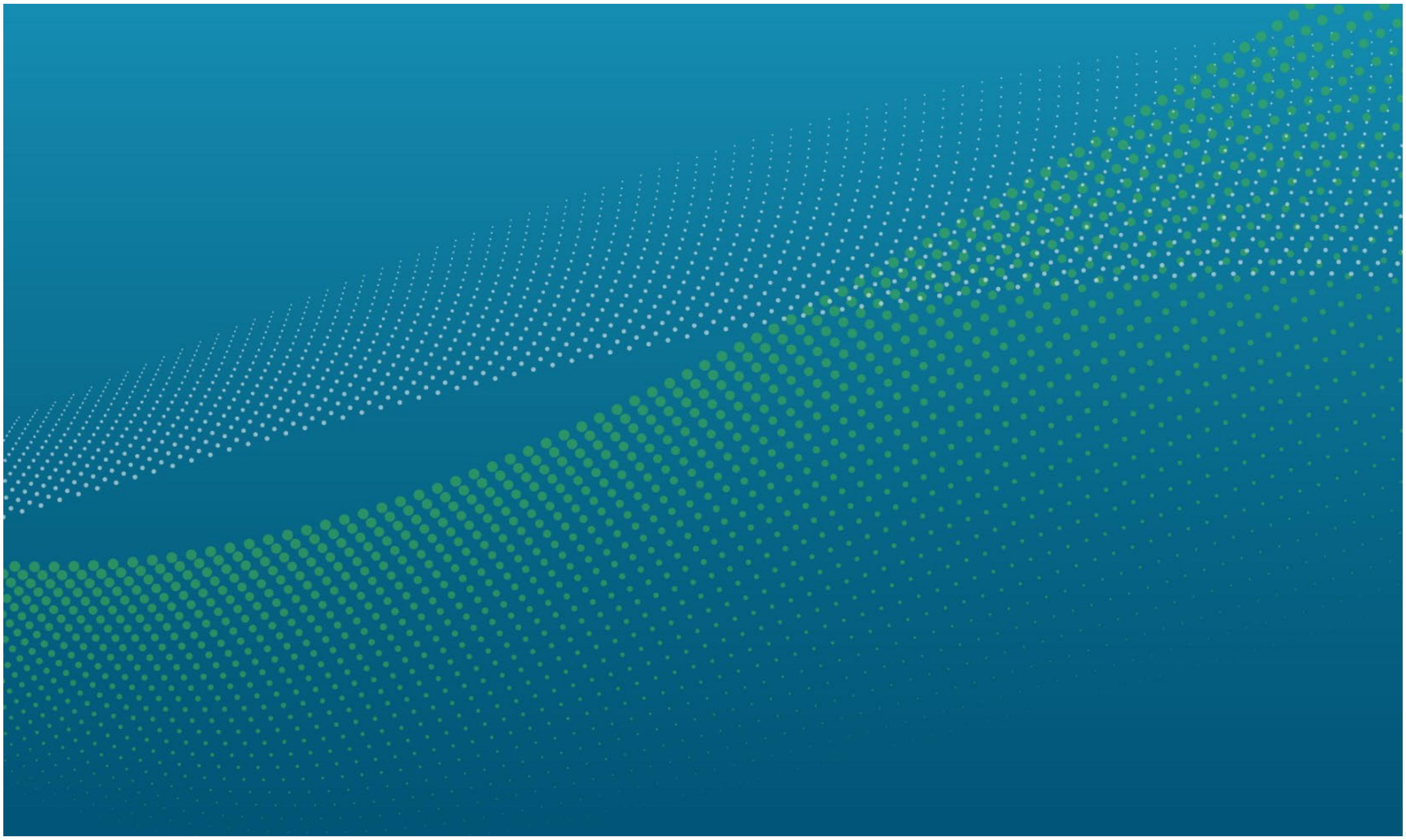

Lifecycle GHG Impacts of C&I Heat Pump Applications in Vermont

EFFICIENCY VERMONT R&D PROJECT: GREENHOUSE GAS REDUCTION

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Introduction

Value to the Customer

As commercial and industrial (C&I) building owners learn more about the value of heat pumps, they look for deeper understanding of associated lifecycle costs. Classically, an energy investment decision boils down to comparing energy and equipment costs in terms of the new equipment's operational efficiency. Under this "simple payback" model, operational efficiency is the sole driver of return on investment.

However, an operational efficiency calculation fails to account for a broader array of actual costs and benefits of heat pumps. Widening the payback analysis scope beyond operational efficiency can contribute to building owners' full understanding of pre- and post-replacement costs with energy efficiency program support. Consideration of costs and risks associated with natural resource extraction, manufacture, transportation / distribution, and disposal contributes to greater awareness of the societal costs of heating system retrofits. However indirect those societal costs might seem to a customer, they are still borne by taxpayers through subsidies to communities affected by the various stages of the equipment's lifecycle.

This study presents an accounting method that suggests a possible standard for assessing the actual, long-term value of heat pump installations specifically, and of energy efficiency and electrification projects in general.

Value to Climate Change Mitigation

Some energy efficiency utilities work towards decarbonization goals in addition to energy efficiency. By supplanting on-site fossil fuel heat with an electric appliance like a heat pump, heating electrification initiatives can improve the cost-effectiveness of a heating system *and* decrease the local carbon intensity of heating across a utility service area. However, to substantiate claims about greenhouse gas (GHG) reduction, it is necessary to extend the system boundaries of electrification and energy efficiency initiatives beyond merely on-site operational efficiency. GHG impacts tend to lie in unexpected places, and they are always wider than the site itself.

Specific Aims

This study provides a method for capturing broader GHG impacts of energy efficiency projects in C&I buildings that supplement existing fossil fuel heating sources with heat pumps. The study has had two aims: (1) to provide insight into the GHG impacts of a common heating, ventilation, and air-conditioning (HVAC) project in a cold climate like Vermont's, and (2) to work through a GHG accounting method for electrification and energy efficiency work.

Considerations

The GWP100 Standard

Any attempt to distill the costs and benefits in terms of GHG reduction is only as successful as the standard it uses to measure carbon equivalence, or CO_2e. Chemically, some emissions have heattrapping effects that decay over time, whereas others (including CO_2 itself) maintain a constant effect for centuries. This study has taken a conservative approach in employing the GWP100 standard (global warming potential at one hundred years). At the one-hundred-year mark, what equivalent mass of CO_2 emissions would have had the same effect on global warming as the gas in question? The answer is given in terms of equivalent mass of CO_2, or CO_2e.

In its research and accounting, the study team could not always discern whether a source used GWP100 or GWP20. In cases where the source offered values from both standards, the study team chose GWP100 value. This paper's Conclusion addresses the impact of selecting GWP20 vs. GWP100 carbon equivalence on the study's results.

The GHG Protocol and Scopes

Quantifying the GHG impacts of a mechanical system retrofit project requires a valid, reliable method for differentiating sources of emissions related to project activity. To that end, this study adopts terminology from the GHG Protocol,[1] specifically from the Corporate Value Chain Standard, to delineate among three sources or *scope*s of GHG emissions.[2]

Assigning emissions to one of the three scopes requires a frame of reference. The frame of reference for this study evaluates two conditions for heating within four unrelated, existing buildings. The two conditions are: (1) a baseline condition in which the owner continues to use only the existing boiler for space heat (and, at some point over the analysis time frame, replaces the boiler if necessary), and (2) an efficient condition in which the owner buys and installs heat pumps to use in conjunction with the existing boiler for space heat. The emissions of these conditions can then be "scoped" as follows:

Scope 1 emissions are "point-source" direct emissions from the site itself. In this study, Scope 1 emissions are:

- boiler fuel combustion emissions
- fugitive emissions from leaks in heat pump refrigerant lines[3] due to system operation and installation

Scope 2 emissions come from the electric grid. This study accounts for the following Scope 2 emissions:

- electric source emissions attributed to the boiler heating system's electrical components
- the same for the operation of the specified heat pumps

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[1] Greenhouse Gas Protocol is a joint activity of the World Resources Institute and the World Business Council for Sustainable Development. It has established "comprehensive global standardized frameworks to measure and manage GHG emissions from private- and public-sector operations, value chains, and mitigation actions." https://ghgprotocol.org/.

[2] The study team has determined the accounting standard's distinction between *primary* and *secondary* emissions to be less useful than the Scope 1, 2, and 3 emissions framework described in the paragraphs following this footnote reference.

[3] The EPA bases its guidance to corporations on the GHG Protocol. See EPA (U.S. Environmental Protection Agency), n.d. "Direct Fugitive Emissions from Refrigeration, Air Conditioning, Fire Suppression, and Industrial Gases." A Greenhouse Gas Inventory Guidance document of the U.S. EPA Center for Corporate Climate Leadership. https://www.epa.gov/sites/production/files/2015-07/documents/fugitiveemissions.pdf.

Scope 3 emissions refer to the embodied carbon of equipment, materials, and consumables purchased and installed or consumed under the reference conditions. Scope 3 includes lifecycle emissions from the extraction of natural resources, manufacture, purchase, installation, and commissioning of equipment and materials. Scope 3 emissions considered under this study are:

- emissions due to the production of boiler fuel
- embodied carbon of the heat pumps and system components
- embodied carbon of a new boiler in cases where one would be required over the analysis time frame

Note that most of these emissions are recurring, but some of the Scope 3 emissions are fixed.

Precision and Sensitivity

This study's list of Scope 1, 2, and 3 emissions is far from comprehensive. Scope 3 emissions especially have far-reaching effects that can be difficult to isolate and measure as a researcher attempts to attribute effect to cause. The team had to decide which factors to pursue for a more precise calculation, and which to leave as estimates, in light of the fact that the GHG impact of one input material can vary from the next by orders of magnitude. To illuminate the sensitivity of the results to some of these input factors, this paper provides a table of factor effects, under Results (see Table 4). One measure of this study's success was the determination of which factors have the largest effect on the analysis results.

Methods

Project Portfolio Sample and Mechanical Systems

This study chose four projects intended to represent a cross-section of C&I heat pump applications – a school, a storage facility, plant offices, and retail shop. The small differences among these projects provided degrees of freedom to explore how carbon impacts vary by calculation method, and by real-world application conditions.

In all four projects, the building owners partnered with contractors, engineers, and/or energy consultants to specify ductless, split-system heat pumps to supplement building heat from pre-existing fossil fuel boilers. This type of heating retrofit project is common in cold climates like Vermont's. Ductless heat pump systems comprising an outdoor unit, one or multiple indoor "heads," refrigerant lines connecting the units, and electronic controls are installed at various locations throughout the facility. Because heat pump performance generally wanes *and* building heating loads increase as outdoor temperatures drop below 0°F, the boiler remains in place (along with its entirely separate network of piping, pumps, and radiators) to deliver simultaneously, with the heat pumps, hot water or steam throughout the facility on very cold days.[4] The building owner has now moved to a primarily electric heating source that is nominally lower in its carbon emissions.

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[4] In such cases, any mechanical ventilation systems are either separate from the heating system or absent altogether. Also of note: this study did not consider all-electric buildings, or buildings in which heat pumps displaced a boiler or furnace entirely.

Table 1 summarizes the site-specific resources consulted by the study team for each project analysis.

Table 1. Study team's project-specific resources, by site

School	Storage	Plant offices	Retail	Resources consulted by study team
	X	X	X	Site visit notes from program staff
X	X	X	X	Correspondence between project decision makers and program staff
	X		X	Boiler fuel consumption records
X		X		Architectural and engineering drawings for heat pump installations
X	X	X	X	Performance specifications across temperature & load for heat pump models
X	X	X	X	Manufacturer-specified installation parameters for heat pump models
X	X	X	X	Heat pump manufacturer material balance reports

Table 2 shows relevant details for each site and describes the heat pump systems.

Table 2. Heating system details at each site

			Heat pumps				
	Heating square feet	Boiler fuel	Number of indoor heads	Split-system types	Nominal capacity (MBH)	Refrigerant charge (pounds)	Product weight (pounds)
School	20,100	Oil	30	Single & multi-head	440	150	5,570
Storage	16,850	Oil	10	VRF[5]	144	36	1,900
Plant offices	12,480	Propane	13	VRF & single-head	132	71	1,920
Retail	10,480	Oil	6	Single-head	102	22	1,010

Heating Load Calculations

In three of the four cases, the study team used building energy modeling (BEM) software to model boiler heating loads at hourly intervals across the 2019-2020 heating season.[6] The BEM outputs provided load shapes that captured short-term load dynamics such as the morning rush of activity as a building emerges from nighttime setback.

The plant offices presented a unique case. They had one external wall, but were otherwise situated inside the plant, where ambient space heat or heat from nearby industrial processes provide a large portion of space heating. The heat pump system had little or no setback because the plant saw similar

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[5] VRF is short for "variable refrigerant flow" and is a type of heat pump system described in subsection "Direct Emissions of Heat Pumps."

[6] OpenStudio comprises free, open-source, cross-platform software applications for building energy modeling. A team at VEIC has built inputs for building types, size and shape, window-to-wall ratio, and locational weather data such as temperature and wind speed.

occupancy levels around the clock. Lack of convenient BEM input data for these spatial conditions, as well as the minimized importance of setback, led the study team to choose an analytical "UA" method[7] rather than BEM. To make a conservative estimate, the team chose a design load of 8 Btu/hour per square foot at -13°F wet bulb outdoor air temperature, decreasing linearly to no load at 55°F.[8] The team then applied this load formula across the 2019-2020 temperature profile at the plant's location, estimating an additional 15 percent heat loss through the insulated steam pipe from the boiler room to the offices.

For all four projects, the study team modeled the efficient condition as follows:

1. Used heat pump performance specifications across load and outdoor air temperature[9] (OAT) to calculate a blended system coefficient of performance (COP) at various OATs, using heat pump system fractional capacity and estimated duty cycle to approximate part-load conditions.
2. Generated a regression formula to model system COP across outdoor air temperatures.
3. Applied this formula to the building's heating load over the season. Where the heat pump system can't meet the load, fill in the remainder with boiler heat.[10]

This method approximated boilers and heat pumps working in tandem under a lead-lag control scheme, where the boiler thermostat simply would have been set to a lower indoor set-point than that of the heat pumps. The study team did not model control schemes where the system switches from heat pumps to boiler at a specified outdoor air temperature.

Once the heating loads were calculated and baseline and efficient heating had been modeled, the study team turned to emissions scopes.

Scope 1: Direct Emissions

Direct Emissions of Fossil Fuel Boilers

Direct emissions of boiler fossil fuel combustion were the simplest to calculate. The BEM software incorporates typical boiler combustion and system heat transfer efficiencies based on building type. In the case of the plant offices, the team divided the result of the heating load analytical calculation by the plant steam boiler's annualized combustion efficiency, estimated to be 85 percent.

The team then quantified annual emitted pounds of CO_2e by multiplying MMBtu provided over the heating season by the emissions factors for propane or distillate (fuel oil No. 2).[11] In the cases of the

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[7] "UA" is short for $Q=UA\Delta T$, which is a common heat transfer equation used in HVAC engineering.

[8] This study did not include additional cooling loads (air conditioning) provided by heat pumps.

[9] The team consulted the Northeast Energy Efficiency Partnerships' (NEEP's) Cold Climate Air Source Heat Pump List (https://ashp.neep.org/#!/product_list/) and manufacturer product manuals to find performance specifications. Capacity corrections factors were considered where data were available.

[10] Boiler burner efficiency across part-load firing range was not considered under this study. The factors affecting instantaneous boiler efficiency are complex, and the study team did not gather site-specific data necessary to express this factor in a valid way. Table 4 shows the sensitivity of the results to boiler efficiency as an input factor.

[11] U.S. Energy Information Administration, n.d. "Carbon Dioxide Emissions Coefficients." Washington, DC: U.S. EIA. https://www.eia.gov/environment/emissions/co2_vol_mass.php.

retail building and the storage facility, the study team corroborated the BEM heating season output against previous heating season fuel consumption records, with satisfactory results.

Direct Emissions of Heat Pumps

Refrigerants used in heat pumps have infamously high global warming potential, on the order of thousands of times that of CO_2, by mass. Refrigerants exist as gases at atmospheric temperature and pressure; their molecules are relatively small, and leaks can go undetected until a significant portion of refrigerant has escaped. Thus, even a very small refrigerant leak can easily have very large impacts on application emissions.

Split-system heat pumps like the ones surveyed in this study use long refrigerant lines that run for tens or hundreds of feet between walls and above ceilings. This is in comparison to more traditional "packaged" HVAC components like rooftop units or packaged terminal air conditioners, which have total refrigerant line lengths of a few feet at most. Packaged units are readily accessible to service, because the refrigerant is confined to the equipment itself. Further, the installation and commissioning of a split-system heat pump involves crimping refrigerant connections on site. This practice leads to varying quality of the connections (and therefore varying estimated leak rate) when compared to factory-made connections of packaged units. So, even though HVAC equipment has been using refrigerant for decades, split-system heat pumps use more refrigerant *and* are more prone to leaks than packaged HVAC equipment.

Within split-system heat pumps is a group that use variable refrigerant flow technology (VRF). VRF systems are one type of "multi-head" heat pump system that pair several indoor units with just one outdoor unit. VRF supports advanced efficiency measures such as heat recovery and single-zone operation, enabling best-in-class seasonal efficiency. These systems require even more field-crimped connections through junction boxes and longer line lengths to get from indoor head to junction box to the outdoor unit, which is shared by other heads at various indoor locations throughout the building.

As VRF technology matures, contractors and suppliers are re-evaluating its life cycle costs. In a facilities criteria document current through March 2020, the U. S. Department of Defense places special requirements on VRF installations at military facilities for several reasons, two of which are (1) "unknown life cycle costs," including maintenance costs; and (2) EPA requirements to shut down systems that leak above a specified threshold. In a 2017 appendix to the document, the authors estimated an annual leak rate for VRF systems of 25 percent.[12]

The study team found more fugitive emissions data for residential heat pumps and on heat pumps broadly. A 2013 analysis of service logbooks from 528 non-domestic heat pump applications in the United Kingdom found leaks in 9 percent of them, with a median leak rate of 42 percent. The blended average leak rate from these log books was 3.8 percent.[13] The EPA's Test Method for calculating fugitive emissions of heat pumps stipulates a 10 percent annual operational leak rate for heat pumps

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[12] U.S. Department of Defense, 2020. "UFC 3-410-01 Heating, Ventilating, and Air Conditioning Systems with Change 6." *Whole Building Design Guide.* Washington, DC: National Institute of Building Sciences. https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-3-410-01.

[13] Eunomia Research & Consulting, Ltd., and the Centre for Air Conditioning and Refrigeration Research (London Southbank University), 2014. "Impacts of Leakage from Refrigerants in Heat Pumps." London, England: Department of Energy & Climate Change. https://www.ammonia21.com/files/decc-refrigerants-heat-pumps.pdf.

generally.[14] After considering these documents in light of the market adoption of heat pump and VRF technology at the times they were published, the study team decided to use a 5 percent leak rate for single-head units and 20 percent for VRF systems for the results in this study. Table 2 shows the types of heat pump systems used in each case. One of the "annual leak rate" scenarios in Table 3 shows the leak rates assigned to each of the four projects based on ratio of single-head to multi-head units in the installation.

Further, the EPA's GHG Inventory Guidance Document suggests 1 percent of total system charge (weight) leaks upon installation;[15] this amount is accounted for in the results as well.

Scope 2: Electric Source Emissions

Determining the carbon intensity of a unit of electricity is a matter of discretion. Green Mountain Power (GMP), the electric utility that serves all the projects in this study, boasts a 94 percent carbon-free energy generation mix with plans to be 100 percent carbon free by 2025.[16] GMP achieves this mix after both buying and selling energy on the broader New England market, where the number of low-carbon megawatt-hours at any moment is finite. In fact, the "dominant share [of GMP's] supply resources and energy needs all pass through and participate in the market,"[17] which itself has a carbon-free mix closer to 50 percent.[18] At a given moment, then, a low-carbon megawatt-hour bought and used in GMP territory means a high-carbon megawatt-hour is used elsewhere in New England. This notion would justify calculating Scope 2 emissions based on market-wide carbon intensity.

On the other hand, without entities like GMP paying a premium for low-carbon energy, there would be a lesser incentive for low-carbon generation in the first place. Local utilities seeking to reduce the carbon footprint of their portfolios provide demand for low-carbon kilowatt-hours in the broader New England marketplace, which encourages additional renewable generation projects to come online. Moreover, the heat pump projects surveyed in this study take place within a consumer market where GMP provides financial incentives for customers to install heat pumps. If the utility and the customer are paying a premium for low-carbon energy, and the utility is using incentives to encourage customers to electrify their heating loads, then there is even more demand for low-carbon electricity than there

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[14] In November 2014, the EPA released "Greenhouse Gas Inventory Guidance: Direct Fugitive Emissions from Refrigeration, Air Conditioning, Fire Suppression, and Industrial Gases," which offers a method for calculating installation emissions and operating emissions of heat pumps. This method, in turn, is based on the Tier 2 approach from the 2006 IPCC *Guidelines for National Greenhouse Gas Inventories.* The IPCC has since published its *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

[15] U.S. EPA, 2014. "Greenhouse Gas Inventory Guidance: Direct Fugitive Emissions from Refrigeration, Air Conditioning, Fire Suppression, and Industrial Gases." Washington, DC: EPA. https://www.epa.gov/sites/production/files/2015-07/documents/fugitiveemissions.pdf.

[16] GMP (Green Mountain Power), n.d. "Energy Mix." Colchester, VT: GMP. https://greenmountainpower.com/energy-mix/.

[17] GMP, 2019. *2018 Integrated Resource Plan*. Colchester, VT: GMP: 3-2. https://greenmountainpower.com/wp-content/uploads/2019/12/2018-Integrated-Resource-Plan.pdf.

[18] ISO New England, 2020. *2018 ISO New England Electric Generator Air Emissions Report*. ISO New England, Inc. Holyoke, Massachusetts, ISO New England., https://www.iso-ne.com/static-assets/documents/2020/05/2018_air_emissions_report.pdf.

would have been without the local utility. Under this framing, it is defensible to calculate Scope 2 emissions using the local utility resource mix.

GHG impacts of residential heat pumps' electricity use in Vermont across the heating season has been explored already in a 2019 Efficiency Vermont paper.[19] The authors showed that heat pump Scope 2 emissions factors vary by time of day, and time of year. During a single day, the electric source emissions factor of a residential heat pump, measured in mass per hour, can vary by 2.5 times. This variability is due to a confluence of causes: (1) the efficiency of heat pumps drops as temperatures drop; (2) a building's heating load increases as temperatures drop; and (3) on some extremely cold mornings, the grid operator will draw on oil for the morning peak electric supply as natural gas is diverted to heating applications.

Because of this heavy peak-coincidence factor, the authors showed that during an especially cold January peak, heat pump electric use on the grid operated by the regional transmission organization, ISO New England, can be more carbon intensive than on-site natural gas use or even oil heat use for a few hours.[20] Notably, that study concludes that local electric utility resource mix information would be appropriate for a carbon intensity study of electric applications in Vermont, especially where a local distribution utility pays a premium for low-carbon energy. [21] However, although GMP makes available its annualized average resource mix data, the time-series generation data to capture any short-term carbon intensive peaks are not publicly available.

An additional consideration with peak coincidence is marginal power. If a customer is adding new electric demand to the grid—which is the case for the heating electrification projects in this study—then it is reasonable to deem the heat pumps responsible for the marginal increase in electric demand during the first few heating seasons, or possibly even over the life of the heat pump. Rather than claiming the Scope 2 emissions of the electric grid at large, then, the heat pumps should claim the Scope 2 emissions of the additional electric supply required to meet the peak demand, which is very often a more carbon-intensive "peaker plant." Even as local utilities move towards a carbon-free generation mix, peak-coincident space heating loads without any load management strategies will continue to stress utility decarbonization initiatives.

The choice of whose resource mix to use, whether to use static or dynamic resource mix data, and whether to use blended or marginal emissions factors all play significant roles in calculating the Scope 2 emissions of heat pumps. It remains to be seen how this variable factor, even at maximum and minimum values, compares to heat pump GHG impacts of Scopes 1 and 3.

With respect to Scope 2 emissions, this study chooses to display results for each of the four projects using emissions calculated with two standards: 1) GMP aggregate generation mix average from 2017 to 2019, and 2) ISO New England marginal generation mix from the 2019-2020 heating season. These two input sets offer highest case (regional marginal) and lowest case (local aggregate) side by side.

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[19] A 45-page report of several research and development projects carried out in 2019 contains an article on estimates of real-world carbon emissions from several different residential heating methods used in Vermont. See Fink, Michael, and Asa Parker, 2019. "Appendix 2: Calculated Carbon Emissions from Heating through the 2018 – 2019 Vermont Winter." *2019 Greenhouse Gas Taskforce,* Efficiency Vermont Report. Winooski, VT: VEIC: 11-23. https://www.efficiencyvermont.com/Media/Default/docs/white-papers/2019_RD_GHG_taskforce.pdf.

[20] Fink and Parker, "Calculated Carbon Emissions," 2019, p. 20.

[21] Fink and Parker, "Calculated Carbon Emissions," 2019, p. 21.

For boilers, the team estimated a small electric load associated with combustion components and hydronic circulation pumps required to loop hot water through the system. These components typically use only a small fraction of the electricity used by heat pumps. The results show their impact under Scope 2 emissions for boilers, where applicable.

Scope 3: Embodied Carbon

Embodied Carbon of Heat Pumps

Under the GHG Protocol, projects that require the purchase and installation of new equipment will then claim the emissions from materials extraction, production, transportation, and potentially the disposal of that new equipment as Scope 3 emissions. These "secondary effects" are chiefly what is meant by *supply chain emissions*, *value stream emissions*, or *embodied carbon*.[22]

In evaluating construction materials for new buildings, contractors can consult environmental product declarations (EPDs) to account for the embodied carbon in these new materials.[23] EPDs for heat pumps are much less common, but the study team has derived an EPD-like embodied carbon metric for heat pumps by using publicly available, company-wide material balance reports of heat pump manufacturers. The study team sought material balance reports from corporate divisions responsible for manufacture and sale of heat pumps, rather than reports for the corporations at large—for example, Fujitsu General Group, rather than Fujitsu; and Mitsubishi Electric, rather than Mitsubishi.[24, 25]

For a heat pump manufacturer, the team could then estimate pounds of CO_2e per pound of product by summing all the manufacturing business group's reported GHG emissions across one year, and then dividing the sum by the weight of all products sold that year.[26] In cases where the weight of all products sold was not published, the team used the weight of all raw material inputs, minus the weight of all published waste streams.

In this study, the resulting Scope 3 emissions figure for heat pumps ranges from 3.8 to 5.6 pounds of CO_2e per pound of product sold, depending on the manufacturer. Notably, this pound-for-pound factor represents a blended estimate that applies to *all* products of the business group, not specifically

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[22] World Resources Institute and World Business Council for Sustainable Development, n.d. https://ghgprotocol.org/.

[23] EPDs are independently verified and registered documents, a Type III declaration under the International Organization for Standardization's ISO 14025 for environmental labels and declarations. They clearly articulate comparable information about the life cycle environmental impact of a product. They are voluntary documents; holding an EPD for a project or product does not signal environmental superiority. See The International EPD® System: https://www.environdec.com/What-is-an-EPD/.

[24] Office of CSR Promotion and Environment, Environmental Administration Division, Fujitsu, 2019. *Environmental Report 2019.* Kanagawa, Japan: Fujitsu General Limited: 33-34. https://www.fujitsu-general.com/shared/pdf-f000-environmental-report-2019-en-02.pdf.

[25] Corporate Environmental Sustainability Group, Mitsubishi, 2020. "Environmental Data: Material Balance." *Environmental Report 2020.* Tokyo, Japan: Mitsubishi Electric Company: 39-40. https://www.mitsubishielectric.com/en/sustainability/environment/report/index.html

[26] Although the study team excluded transportation emissions, for lack of sufficient information about distribution methods, including them would have offered even greater accuracy of life cycle cost. The team used product information for Mitsubishi heat pumps from Mitsubishi Electric Group. For Daikin, product information came from that company's international group, Daikin Global. Both company statements contained information on products in addition to heat pumps.

heat pumps. To estimate the total embodied carbon of the installed heat pump systems, then, the team consulted each component's engineering data for its weight, summed the weights of all the heat pumps at the site, and multiplied the sum by this CO_2e per pound of product sold.

These estimates are not refined enough to differentiate between the carbon footprint of one manufacturer or the other; rather, they are intended to provide a sense of the Scope 3 emissions of HVAC equipment in general.

Embodied Carbon of Heat Pump System Components

Copper tubing. The refrigerant lines connecting indoor heat pump heads to outdoor units are generally made of copper tubing. A survey of cradle-to-gate life cycle analyses (LCA)[27] of copper showed values ranging from approximately 2 to 8 pounds of CO_2e per pound of copper from primary sources (material extraction), or from ½ to 2 pounds for copper from secondary sources (recycling), where the variability depended primarily on source location. A 2019 LCA of copper tubing, which has a higher carbon footprint than raw copper because it requires more steps to process, calculated 3.37 pounds of CO_2e.[28] This is the value the study team used.

The study team calculated that the heat pump installation projects used copper tubing in amounts ranging from approximately 200 to 1,000 pounds per site.

Refrigerant. This study has accounted for refrigerant leaks as Scope 1 emissions and the embodied carbon of heat pump appliances and copper piping as Scope 3 emissions. What remains are GHG emissions from the manufacture of the refrigerant. Although some heat pump components ship with a factory charge, the study team estimated that full scope of upstream emissions belonging to refrigerant manufacture are not accounted for in the material balance reports of the heat pump manufacturers. After a review of the literature, the study team chose an embodied carbon metric of 70 pounds of CO_2e per pound of R-410A refrigerant produced.[29, 30]

Embodied Carbon of a New Boiler

In the case of the retail building, the building owner would have needed to purchase a new boiler if they had chosen not to install heat pumps. For this reason, the retail building's baseline condition results include the embodied carbon of a new boiler.

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[27] Nilsson, Anna Ekman, Marta Macias Aragonés, Fatima Arroyo Torralvo, Vincent Dunon, Hanna Angel, Konstantinos Komnitsas, and Karin Willquist, 2017. "A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources." *Minerals* (7) 9: 168. https://www.mdpi.com/2075-163X/7/9/168.

[28] Wildnauer, Maggie, 2019. *Life Cycle Assessment of Copper Tube and Sheet.* For the Copper Development Association, by thinkstep AG. https://www.copper.org/environment/sustainability/pdfs/copper_life_cycle_assessment_tube_and_sheet.pdf.

[29] A 2020 NREL study of the U.S. refrigerant supply chain indicates an embodied carbon metric for hydrochlorofluorocarbon HCFC-22. HCFC-22 (also known as R-22) is being phased out in accordance with the 1970 Clean Air Act because of the substance's ozone-depleting potential. R-22 was not used in any project in this study. https://www.nr el.gov/docs/fy20osti/70207.pdf

[30] The EPA's Greenhouse Gas Reporting Program shows quantities of reported HFC supplies as well as production emissions, both in terms of tons of CO_2e. The study team used this supply chain data to make the rough estimate of 70 lb/lb CO_2e for R-410A. https://www.epa.gov/ghgreporting/fluorinated-greenhouse-gas-emissions-and-supplies-reported-ghgrp

A 2019 Efficiency Vermont research paper calculated the embodied carbon of a 448-lb residential boiler by summing the embodied carbon of the boiler's component materials (mostly steel) with a result of 746 pounds CO_2e.[31] Using a similar method, this study estimated that a new 130-MBh boiler for the retail facility would have weighed 700 pounds, which amounts to approximately 1400 pounds CO_2e.

Embodied Carbon of Boiler Fuel

Boiler fuel remains a recurring material input to both the baseline and the efficient conditions in this study. And whereas the study has certainly accounted for emissions from the combustion of boiler fuel as Scope 1 emissions, the emissions associated with the *production of boiler fuel* remain unaccounted for. In other words, embodied carbon of boiler fuel is not the same as *heating content*. From the frame of reference of a C&I decision maker, these emissions don't come from the site, but the emissions are required for producing the fuel that will be combusted on site.

The "Greenhouse Gas Emission Intensity of Petroleum Products" provided the CO_2e emissions per unit of heat content of certain fuels produced in the United States.[32] The team simply converted these values to pounds of CO_2e per MMBtu. Notably, propane has a production emission intensity per unit of heating content almost twice that of residential fuel oil.

Discussion

Omitted Factors

The study team omitted several factors from the study. To add value to the full determination of carbon impacts from heat pump installations in the C&I market, a more comprehensive lifecycle analysis of heat pumps in Vermont would account for these factors.

1. **Scope 1: heat pump end-of-life fugitive emissions.** An initiative attempting to quantify the global impact of refrigerants has ascribed nearly 90 percent of all refrigerant fugitive emissions to end-of-life disposal,[33] whereas another study has determined that 90 percent of refrigerant leaks come from operational use (including catastrophic leakage).[14] In terms of customer value, the financial and resource costs associated with evacuating and disposing of a split-system heat pump could easily increase over the heat pump's lifetime, and should be estimated and presented to the decision maker before the project begins. Heat pump

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[31] A 45-page report of several research and development projects carried out in 2019 contains a lifecycle analysis on residential boilers. See Morlino, Lauren, 2019. "Oil and Advanced Wood Heating Lifecycle Analysis for a Vermont Home." *2019 Greenhouse Gas Taskforce,* Efficiency Vermont Report. Winooski, VT: VEIC: 11-23. 24-8.

[32] Elgowainy, Amgad, Jeongwoo Han, Hao Cai, Michael Wang, Grant S. Forman, and Vincent B. DiVita, 2014. "Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S. Refineries." *Environmental Science & Technology (48)* 13: 7612--24. https://pubs.acs.org/doi/10.1021/es5010347.

[33] Project Drawdown cites this estimate from an excerpt from Hawken, Paul, Ed., 2017. *Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming.* New York: Penguin Books. Excerpt at: https://drawdown.org/solutions/refrigerant-management

recycling programs present opportunities for manufacturers and utilities to reduce GHG emissions and achieve climate change mitigation goals.

2. **Scope 1: boiler system efficiency and controls.** This study based assumptions of boiler system efficiency on building type and boiler age. The team did not consider boiler types (condensing versus atmospheric) or maintenance or control efficiency measures; however, these measures do affect boiler performance, and thus would be worth measuring. **Table 4** at the end of this paper shows the estimated sensitivity of the overall results to changes in boiler efficiency.
3. **Scope 1: time-dynamic GWP aspects of hydrofluorocarbon (HFC) refrigerant.** Although this study uses GWP100 and discusses the use of GWP20, more insights might be possible from a formulaic value for real-time global warming effects of R-410A, especially because a study must give results in terms of an arbitrary time frame (1 year, 3 years, heat pump lifetime, 100 years, and so on).
4. **Scope 2: heat pump cooling loads.** All heat pumps surveyed in this study have the added benefit of providing cooled air in the summertime. This study makes a side-by-side comparison of heat pumps with boilers for space heating applications only (see **Figure 1**); to extend the study scope to cooling loads would suggest a baseline condition of boiler plus an air conditioning system. Regardless, the addition of summer peak-coincident cooling loads is a real side-effect of heating system electrification with heat pumps. To building owners, the added benefit of air conditioning makes the case for heat pumps more compelling.
5. **Scope 2: heat pump application performance and right-sizing**. This study assumes the installed heat pumps run according to the manufacturer's performance data. In the retail project, electric and fuel billing data pre- and post-heat pumps reveal this to be a good assumption, but the other cases rely on the modeling and calculation alone. In all, the projects examined in this study show heating season performance factors (HSPF) ranging from 10 to 13. However, it is possible for real-world heat pump performance to vary significantly from the manufacturer specifications, depending on parameters of the building and the installation. The last row in Table 4 shows the average factor effect of a 50% reduction to HSPF.
6. **Scope 3: electricity transmission losses**. A generic loss factor could be applied to all Scope 2 electrical emissions. Real-world factors affecting transmission losses involve proximity of the site in question to city or town centers, as well as the short-term market dynamics governing the purchase or sale of local generation. This study did not apply a transmission loss factor associated with sites or sources. The GHG Protocol notes that "upstream emissions associated with the … transmission or distribution of energy within a grid, are tracked in scope 3, category 3."[34]
7. **Scope 3**: **electric generation natural gas fugitive emissions.** Natural gas makes up a large portion of ISO New England's generation mix, and the study team estimated that upstream natural gas emissions are not included in the grid operator's reported generation emissions used in this study. Estimated methane emissions due to natural gas leaks and venting range

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[34] Sotos, Mary et al., 2015. "GHG Protocol Scope 2 Guidance: An amendment to the GHG Protocol Corporate Standard." World Resources Institute. https://ghgprotocol.org/scope_2_guidance

from 1 to 3 percent, or more.[35, 36] Un-combusted methane has a GWP100 of 25 and a GWP20 of 72 pounds CO_2e. It is worth noting that because a gas distribution pipe must always be pressurized, reducing electricity usage would not necessarily reduce leaks. It is also worth noting that accounting for additional electric grid natural gas fugitive emissions could apply to all scope 3 emissions sources as well, such as the electricity required to refine petroleum or manufacture heat pumps. These complexities informed the decision to omit this factor altogether.

8. **Scope 3: transportation.** This study did not consider emissions from transportation related to either the baseline (fuel truck deliveries) or the efficient condition (contractor and project transportation emissions, raw material and manufacturing transportation emissions). A 2019 Efficiency Vermont study has approximated the emissions of residential fuel truck deliveries as well as the emissions of the delivery of a new boiler.[37]
9. **Scope 3: lifetime effect of boiler moving to part-load.** This study did not address the real effects of relegating a boiler to backup heating. On one hand, this could extend boiler life by reducing its overall load. On the other, setting the boiler to run as "trim" heating supply on top of a heat pump load could apply new load dynamics to the boiler such as short-cycling and partial load heat losses. These new load dynamics could have deleterious effects on boiler life.
10. **Scope 3: disposal.** In addition to the Scope 1 heat pump end-of-life emissions, there are Scope 3 emissions associated with the energy required to destroy, recycle, reclaim, or otherwise dispose of any new material purchased under the baseline or efficient condition. The study team found that some heat pump manufacturers reduced their carbon footprints by participating in product recycling programs, which lowers the Scope 3 "upstream" embodied carbon of heat pumps.
11. **Scope 3: maintenance costs.** This study made no investigation of maintenance costs for boilers or heat pumps, although these costs certainly play a role in a system's overall cost effectiveness values and carbon emissions.

Results

Of the four projects surveyed, the heating load analyses showed that heat supplied by the new heat pumps met a minimum of 46 percent of the seasonal heating load of the facility, and a maximum of 99 percent, with the boiler to take care of the remainder in each case.

Table 3 shows 20-year cumulative emissions (in metric tons CO_2e) for each project, broken out between boiler and heat pumps and divided by scope.

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[35] Alvarez, Ramón et al., 2018. "Assessment if methane emissions from the U.S. oil and gas supply chain." *Science*. https://science.sciencemag.org/content/361/6398/186

[36] U.S. EPA, 2016. "Inventory of U.S. Greenhouse Gas Emissions and Sinks." Washington, DC: EPA. https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

[37] Morlino, 2019. "Oil and Advanced Wood Heating Lifecycle Analysis," 2019, p. 24.

project		generation mix	HFC GWP value	annual leak rate	SCOPE 1 (direct)		SCOPE 2 (electric)		SCOPE 3 (embodied)		TOTALS
					boiler	heat pumps	boiler	heat pumps	boiler	heat pumps	
Small School	boiler only	GMP			1,569	-	13	-	69	-	1,651
	boiler + heat pumps	GMP	100	6.7%	17	195	13	119	0.7	20	364
	boiler + heat pumps	ISONE	20	33%	17	1,511	91	866	0.7	20	2,506
Retail	boiler only	GMP			920	-	6	-	41	-	967
	boiler + heat pumps	GMP	100	5%	496	21	6	27	22	4	576
	boiler + heat pumps	ISONE	20	33%	496	219	46	196	22	4	982
Storage Facility	boiler only	GMP			886	-	4	-	39	-	930
	boiler + heat pumps	GMP	100	20%	305	138	4	47	13	7	514
	boiler + heat pumps	ISONE	20	33%	305	358	32	339	13	7	1,054
Plant Offices	boiler only	GMP			445	-	-	-	49	-	494
	boiler + heat pumps	GMP	100	11.3%	10	153	-	34	1	8	207
	boiler + heat pumps	ISONE	20	33%	10	706	-	249	1	8	974

Table 3. Comparison across 20 years of cumulative emissions, in tons of CO_2e, by scope, pre- and post- heat pump installations, with two post- scenarios given.

Figure 1 shows graphical breakdowns of cumulative emissions after 3-years for each of the project sites. A 3-year time frame shows clearer results for the embodied carbon of heat pumps, which, as a fixed figure, diminishes next to the recurring project emissions as the analysis time frame grows.

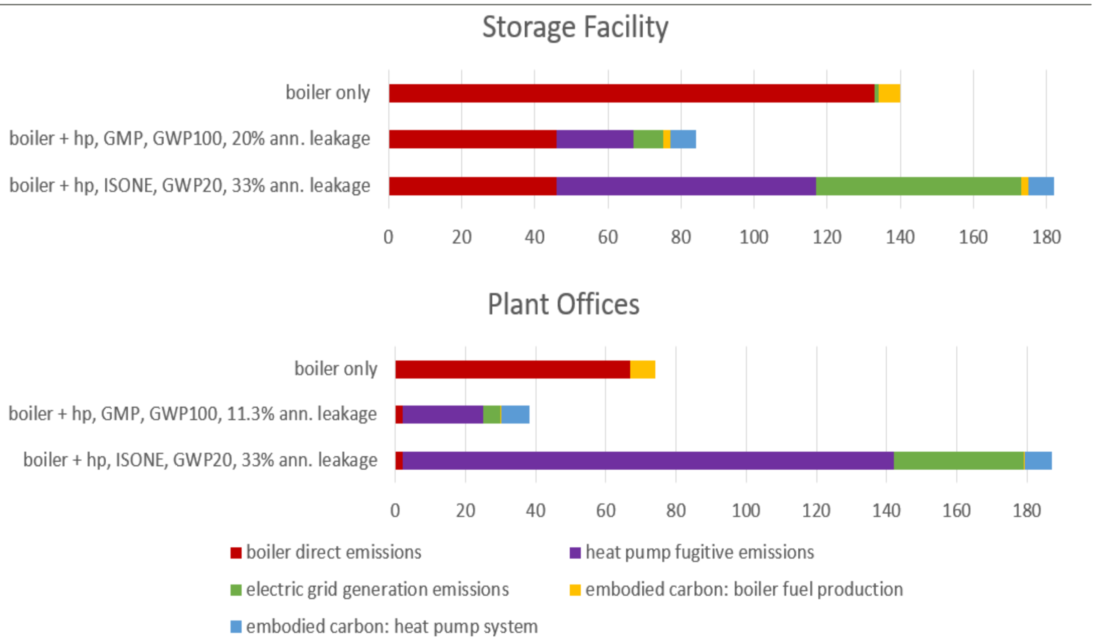

Figure 1. Side-by-side comparisons of each project site's carbon impacts, broken down by factor contributing to emissions.

Table 4 shows the sensitivity of the overall results to various input factors. For example: if this study had chosen to calculate fugitive emissions from heat pumps using GWP20 rather than GWP100, how much would this have changed the results of the carbon savings for one project, on average? Notably, the table shows the effect of one factor in each row, with all other factors held constant, so interactive effects between factors are ignored. For example: by itself, heat pump coefficient of performance (COP) has only a 14% effect on first year project savings, but taken together with the change to use regional rather than local utility generation mix, the factor effect of heat pump COP could jump significantly. A full list of interactive factor effects is outside the immediate scope of this report.

Table 4. Factor effects.

		Average factor effect on single project carbon savings			
		First year		Lifetime estimate	
	Description	Percent	tons of CO_2e	Percent	tons of CO_2e
Refrigerant leak rate	First year varies from 0% to 100% total system charge annually. Lifetime total assumes maximum leakage of 800% system charge over 20 years.	234%	67	73%	538
Marginal power vs. aggregate mix	Regardless of whose electric grid fuel mix to use, analysts must decide between marginal or aggregate carbon intensity.	116%	7	37%	142

Electric grid fuel mix	GMP's average carbon intensity from 2017-2019 was approximately 0.15 pounds of CO_2e / kWh, whereas ISO New England's was closer to 0.8 pounds. Lifetime estimate here assumes GMP moves to 100% carbon-free by 2025 and ISO New England moves to 0.4 pounds CO_2e per kWh by 2040.	62%	13	39%	247
GWP100 vs. GWP20	The 100-year GWP of 1 pound of R-410A is equivalent to 2,088 pounds of CO2e, whereas the 20-year GWP is equivalent to 4,340 pounds.	43%	7	29%	137
Boiler efficiency	Annualized efficiencies of boilers in Vermont can range from >90% for a condensing boiler, down to 75%.	35%	7	26%	142
Heat pump HSPF (COP)	Heat pump performance and installation parameters such as right-sizing.	14%	3	10%	57

Conclusions

Under the most likely scenarios, the results of this study reflect favorably upon supplementing fossil fuel boiler heat with heat pumps in C&I applications as a climate change mitigation strategy. Without heat pumps, fossil fuel combustion for space heating proves unambiguously to be a dominant contributor to GHG emissions. But although the lifecycle emissions of heat pumps are most likely lower than those of a boiler, the calculation of these emissions relies heavily on variable factors. Will the system leak, or not? Whose electric grid generation mix will an analyst use, and will the emissions factors represent marginal or aggregate grid emissions? What GHG equivalence factors will an analyst use for HFC refrigerant? As Figure 1 demonstrates, the answers to these questions can tip the scale between boilers and heat pumps over a 3-year emissions analysis.

Carbon Accounting Guidance Needed

C&I building owners seek to quantify the benefits and potential liabilities of their investments, and energy efficiency utilities will need to evaluate their decarbonization strategies in order to define impacts, set priorities, and collaborate with others. To those ends, energy efficiency utilities should make clear choices between using 1) local utility or regional marketplace generation mix emissions factors, and 2) marginal or aggregate emissions factors.

Additionally, choosing GWP20 rather than GWP100 in an analysis would double the calculated GHG impacts of refrigerant leaks. If building owners think of investments in terms of effects over the lifetime of the new equipment, using a carbon equivalence of GWP at 20 years seems more suited than GWP at

100 years. Alternatively, rather than choosing between the two, utilities could instead use an integrated CO_2e value over measure lifetime, or over the time frame of a given analysis. Because of the chemical properties of HFCs, the GHG impact of HFC refrigerant leaked five years ago is lower than the GHG impact of refrigerant leaked last month. An analysis should be able to integrate these effects over time to deliver a more precise GHG impact over any fixed time frame.

The three factors above have an outsized impact on the results of a lifecycle analysis of heat pumps, and they are questions of calculation methods only. It is time for the quantification of these factors to move from academic papers into the world of contractors, installers, and energy efficiency programs.

The Importance of Refrigerant Management

Although heat pumps enable low- or no-carbon building heating, C&I building owners should count the tens of pounds of HFC refrigerant in their heat pump systems to be a GHG liability. From the limited studies available, the study team learned that most heat pump installations don’t leak substantially, but those that do can easily leak over 40 percent per year. The fact that heat pump efficiency drops as the system loses refrigerant only compounds the GHG impact of refrigerant fugitive emissions. The results of this study reveal that the carbon emissions of a full leak-out of the dozens of pounds of refrigerant in a heat pump system are on par with an entire year’s worth of combusted boiler fuel (thousands of gallons) for the same space.

As awareness grows of this risk, it is possible that regulations on heat pump installations (VRF in particular) will tighten, and operation and maintenance costs could rise with them. While this does pose risk, C&I building owners should remember to compare this potential risk to the certain alternative: without supplemental heat pumps, a boiler will continue to emit tens of thousands of pounds of greenhouse gas into the atmosphere each winter. For R-410A heat pump emissions at GWP100 to outweigh boiler emissions over a heat pump’s lifetime, the heat pump systems catalogued in this study would need to leak all their refrigerant 6 – 10 times. This case seems unlikely, but it is context dependent. A C&I facilities manager could feasibly run a preventive maintenance regime that involves recharging the heat pumps without addressing leaks. The heat pump system could leak some amount each year for its entire life without any performance effects called into question.

As energy efficiency utilities roll out refrigerant management programs, C&I building owners with R-410A heat pump systems should protect their investments with low cost maintenance programs that include leak prevention and testing upon install. These programs could also provide EEUs with more data on leak rates.

Embodied Carbon Cuts Both Ways

At first, the upstream economic activity associated with a heating system retrofit project might appear to have substantial GHG impacts due to the embodied carbon of thousands of pounds of heat pump equipment and copper piping, which are manufactured in parts of the world where the GHG intensity of energy is probably higher than Vermont’s. Thanks to corporate reporting standards, a researcher can quantify the embodied carbon of this project activity and compare it to the GHG savings of the project as a whole. If the analysis scope widens to include Scope 3 embodied carbon of material inputs, then the researcher cannot ignore the upstream emissions of thousands of pounds of fuel, which must be refined and then supplied to the boiler tanks on a recurring basis. This study’s results suggest that after 2-4 years, the embodied carbon of the boiler fuel delivered to the system without heat pumps would outweigh the non-recurring embodied carbon of heat pumps installed for the same application.

Opportunities

There is little question that large corporations are trying to understand the GHG impacts of their activity, because they recognize that GHG emissions contribute to environmental and climate problems affecting their bottom lines. Although they understand Scope 1 and Scope 2 emissions, they have become increasingly interested in accounting for Scope 3 emissions. Utility efficiency programs frequently offer incentives with the express purpose of reducing Scope 1 emissions from combusted fuel, and Scope 2 emissions from electrical efficiency. However, such programs rarely consider Scope 3 emissions, especially from the process of purchasing goods associated with implementing these efficiency measures.

While this study demonstrates that Scope 3 emissions of installed equipment are not a major player in overall GHG impacts of some electrification projects, this may not be the case for all utility projects, especially for energy efficiency projects that reduce electricity usage in a utility service area with an increasingly carbon-free generation mix. Equipment lifetimes, disposal, and materials manufacturing all play roles, and there is opportunity for EEUs to repurpose the tools used in this study to quantify GHG impacts of nearly any energy efficiency or electrification project.