Assessing the Electrical Grid Greenhouse Gas Impact of Strategic Electrification

Efficiency Vermont R&D Project: Greenhouse Gas Reduction

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Contents

Executive Summary

The Vermont Global Warming Solutions Act set aggressive targets for reducing statewide greenhouse gas (GHG) emissions by 2025, 2030, and 2050.[1] To meet this goal, Efficiency Vermont supports adding electric vehicles, heat pumps, and heat pump water heaters in the state. This project explores the GHG impact of some of these, and other, strategic electrification measures.

Using three data analysis approaches, the author developed measure-specific carbon emissions heatmaps based on the GHG impact associated with electrical efficiency measures. The heatmaps accounted for both the reduction in GHG from operational electrical energy efficiency improvements, and the GHG increase associated with higher electrical consumption when fuel switching, including time of use–based marginal[2] electricity generation to meet the intensified demand.

This research provides powerful visualizations of the GHG emissions of electrification measures and how those measures may be best controlled to improve grid performance and carbon savings. Stakeholders may use the heatmaps to inform flexible load management programs optimizing energy and GHG savings, and resulting in strategic, beneficial electrification.

GHG emissions load shapes and heatmaps can help eco-conscious customers tailor their own consumption to minimize carbon emissions.

Seeing the associated carbon emissions from electrification measures enables Efficiency Vermont to optimize program designs for maximizing energy efficiency and minimizing carbon pollution. To achieve the highest accuracy pollution assessment of Vermont power customers, Efficiency Vermont needs time-resolved fuel mix and marginal fuel information from Vermont distribution utilities.

A proposed next step is to develop a self-service web-based application for creating these carbon impact visualizations on demand for portfolio-wide program design and evaluation.

[1] Vermont General Assembly, Act No. 153: An act relating to addressing climate change, also known as The Vermont Global Warming Solutions Act. Section 3, 10 VSA, § 578(a)(1), (2), and (3). 2020. https://legislature.vermont.gov/Documents/2020/Docs/ACTS/ACT153/ACT153%20As%20Enacted.pdf.

[2] Marginal electricity generation / marginal fuel is the time-specific energy source used to meet current increases or decreases in demand.

Introduction

Vermont must reduce greenhouse gas (GHG) emissions to 26% below 2005 levels by 2025, 40% below 1990 levels by 2030, and 80% below 1990 levels by 2050.[3] To meet the 2030 goal, the Vermont Energy Action Network (EAN) proposes adding more than 160,000 electric vehicles, 250,000 heat pumps, and 245,000 heat pump water heaters in the state.[4] This project explores the GHG impact of these, and other, strategic electrification measures, and is intended for stakeholders developing electrification and flexible load management programs.

Methodology

The author developed measure-specific carbon emissions heatmaps based on the GHG reduction associated with operational electrical energy efficiency improvements, and the GHG increase associated with higher electrical consumption including time of use–based marginal electricity generation to meet the intensified demand.

The author presents three approaches for data analysis:

1. **Measure-specific carbon savings shapes:** Combine measure-specific energy savings shapes with electricity fuel mix and emissions data to describe carbon emissions savings due to electricity reduction.
2. **Measure-specific carbon pollution shapes:** Combine high-interval utility meter data with electricity fuel mix and emissions data to describe carbon emissions due to electricity consumption.
3. **Whole-building carbon pollution shapes:** Combine building load-shape data with fuel mix and emissions data to describe carbon emissions.

DATA SOURCES

In Vermont, distribution utilities' annual average fuel mixes are generally much cleaner than those of the overall electricity production fleet in New England. Figure 1 compares different recent fuel mixes from Independent System Operator–New England (ISO-NE), Green Mountain Power (GMP), and Vermont Electric Coop (VEC).

[3] Vermont General Assembly. Act No. 153: An act relating to addressing climate change, also known as The Vermont Global Warming Solutions Act. Section 3, 10 VSA, § 578(a)(1), (2), and (3). 2020. https://legislature.vermont.gov/Documents/2020/Docs/ACTS/ACT153/ACT153%20As%20Enacted.pdf.
[4] Energy Action Network. "Annual Progress Report for Vermont 2020/2021," 2021. https://www.eanvt.org/tracking-progress/annual-progress-report/2021-annual-progress-report/.

Figure 1: Recent fuel mix information for GMP, VEC, and ISO-NE[5]

After renewable energy credits (RECs), VEC's 2019 fuel mix is more than 85% low carbon and GMP's is nearly 100% low carbon. Unfortunately, time-resolved data for either of these sources are unavailable, and the ISO-NE generation fuel mixes used in this analysis are much dirtier than GMP's or VEC's. GMP and VEC both likely buy electricity off the wider ISO-NE grid during periods when load is unexpectedly high. During these periods, utilities can use the fuel mix of the ISO-NE grid to inform decisions involving demand response programs or efficiency measures attempting to minimize carbon emissions until the Vermont-specific utility data are made available.

This report provides results using fuel mix averages representing baseload energy consumption and associated carbon, and marginal fuel mix peaks representing peak load energy consumption and associated carbon.

Measure energy consumption data come from the National Renewable Energy Laboratory (NREL) load-shape library,[6] Vermont-specific advanced metering infrastructure (AMI) data

[5] VEC fuel data: https://vermontelectric.coop/electric-system/power-supply (accessed October 20, 2021). GMP fuel data: https://greenmountainpower.com/energy-mix/ (accessed October 20, 2021). ISO-NE data determined from 2018–2020 data retrieved from ISO-NE's API (https://webservices.iso-ne.com/docs/v1.1/).
[6] National Renewable Energy Laboratory, "End-Use Load Profiles for the U.S. Building Stock" https://www.nrel.gov/buildings/end-use-load-profiles.html (accessed October 20, 2021).

reported to Efficiency Vermont by local utilities, and efficiency end use load profiles currently used in Vermont's Technical Resource Manual.

The calculations and data in this report are from 2018 through 2020. Readers examining this report may have questions about when there were particularly clean or dirty weeks on the New England grid, or whether a particular month included a cold snap or heat wave. For reference, there are general plots for temperature and grid cleanliness in Appendix A. Another time-based event influencing the carbon footprint of the grid is the annual refueling of the nuclear power plants in New England, often occurring in April.

Results

Example results for each analysis approach follow with additional results provided in Appendix B and Appendix C.

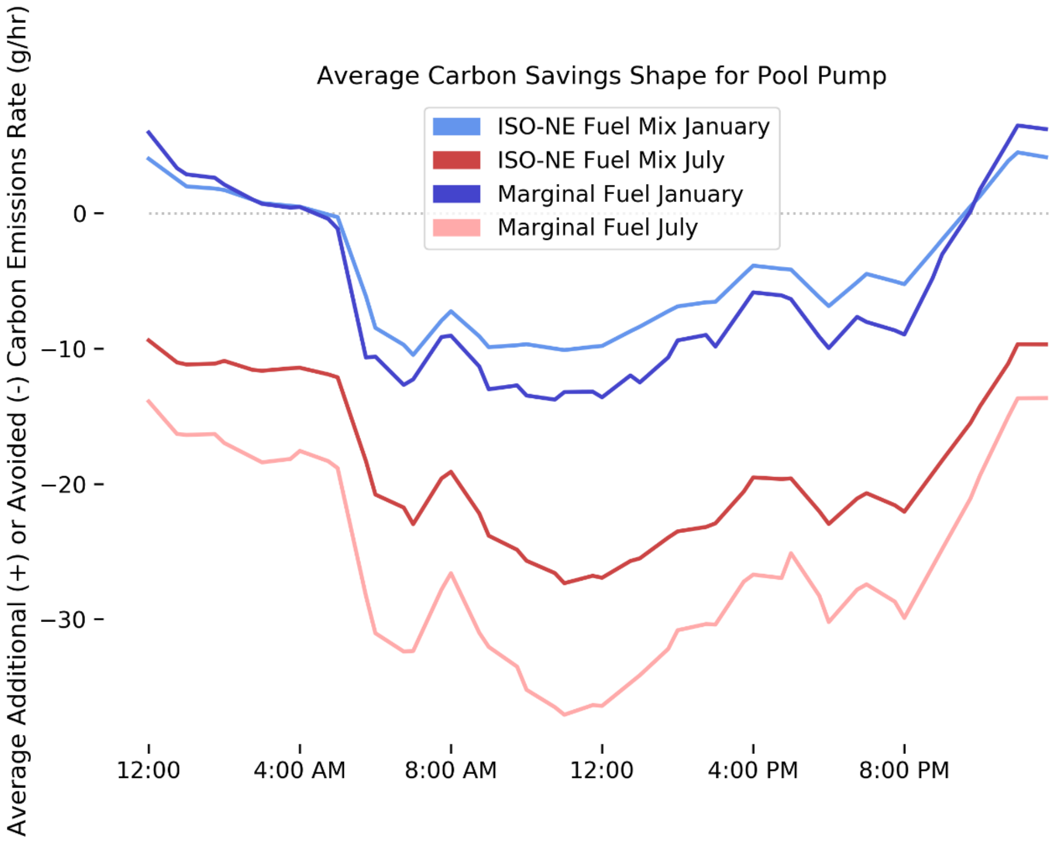
MEASURE-SPECIFIC CARBON SAVINGS SHAPES

Energy savings shapes show at what time of day energy is being saved. Multiplying the measure-specific energy savings of each 15-minute period over the course of a year by the estimated emissions rate of electrical generation on the grid produces a carbon emissions savings shape that reveals when the installation of an efficiency measure is reducing or contributing to carbon emissions on the New England electric grid.

Pool Pumps

Figure 2 charts a carbon emissions savings shape for an efficient pool pump installation. Note the convention on the y-axis: Negative values represent pollution savings over the pre-installation condition and positive values represent additional pollution above the pre-installation condition.

Figure 2: Pool pump savings shapes by ISO-NE fuel mix and marginal fuel averages for January and July



Each line on the plot in Figure 2 represents an average carbon emissions change after installation of an efficient pool pump. For example, consider the light red line (Marginal Fuel July). This line is showing the average savings in carbon emissions rate based on a pre-post time-of-week and temperature regression model for a pool pump installation. A value of −28 on the light red line at 8:00 AM means that, on average, an efficient pool pump installation lowers the emissions rate of carbon by 28 grams/hour if you use the marginal fuel. Of course, pool pump installations tend to save a lot more emissions in the summer (red lines) than in the winter (blue lines) because most pools in Vermont are not open in the winter.

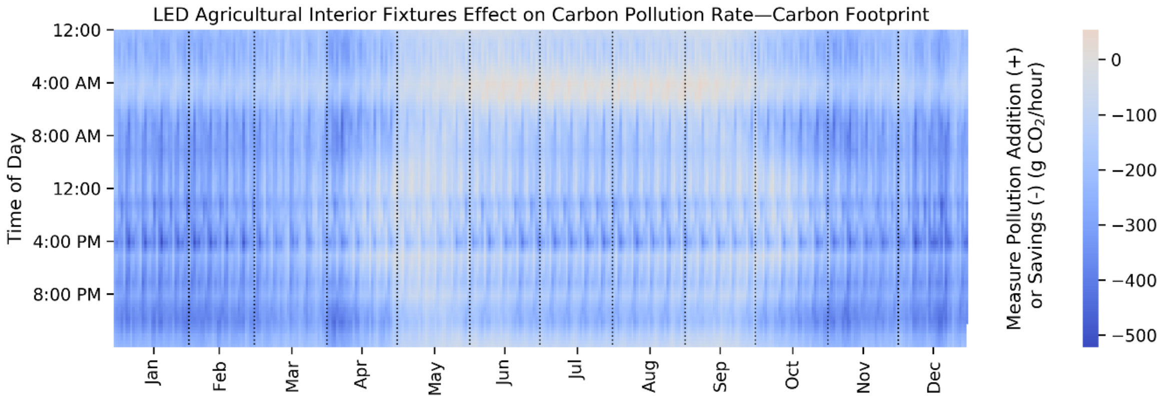
Conditioned Environment Agriculture

Another interesting representation of the ISO-NE emissions data combined with efficiency measure savings data is a heatmap shown in Figure 3. Using 2020 ISO-NE data, this heatmap shows the average additional and avoided carbon emissions over the course of the year due to installation of LED agricultural interior fixtures. The most saturated blue color shows the times of greatest avoided emissions, and white shows times of no additional emissions.

The most intense avoided carbon emissions occur when the new efficiency measure is saving the most electricity *and* when the grid is at its highest carbon intensity. LED agricultural fixtures appear to be avoiding emissions at the highest rate from January through mid-April and from November through December. This makes sense as these are the times of the year when

Vermont is least suitable for outdoor growing and farmers will rely most heavily on interior lights for growing.

Figure 3: Heatmap of avoided (blue) emissions due to installation of LED agricultural interior fixtures



Accounting Methods Matter

"15 Minute" methods calculate an emissions savings or addition for every 15 minutes over a calendar year and sum the result. "Average Marginal" methods use the average ISO-NE emissions rate and multiply that number by each savings shape 15-minute period for the entire year. Figure 4, Figure 5, and Figure 6 summarize the net annual expected carbon emissions savings or additions in the electricity grid because of a single installation of a given efficiency measure using these two accounting methods.

For clarity on the plots, this paper separates the summary slides into three groups depending on the magnitude of the measure's impact: low, medium, or high.

Figure 4: Change in carbon emissions by measure and accounting method—high-impact measures

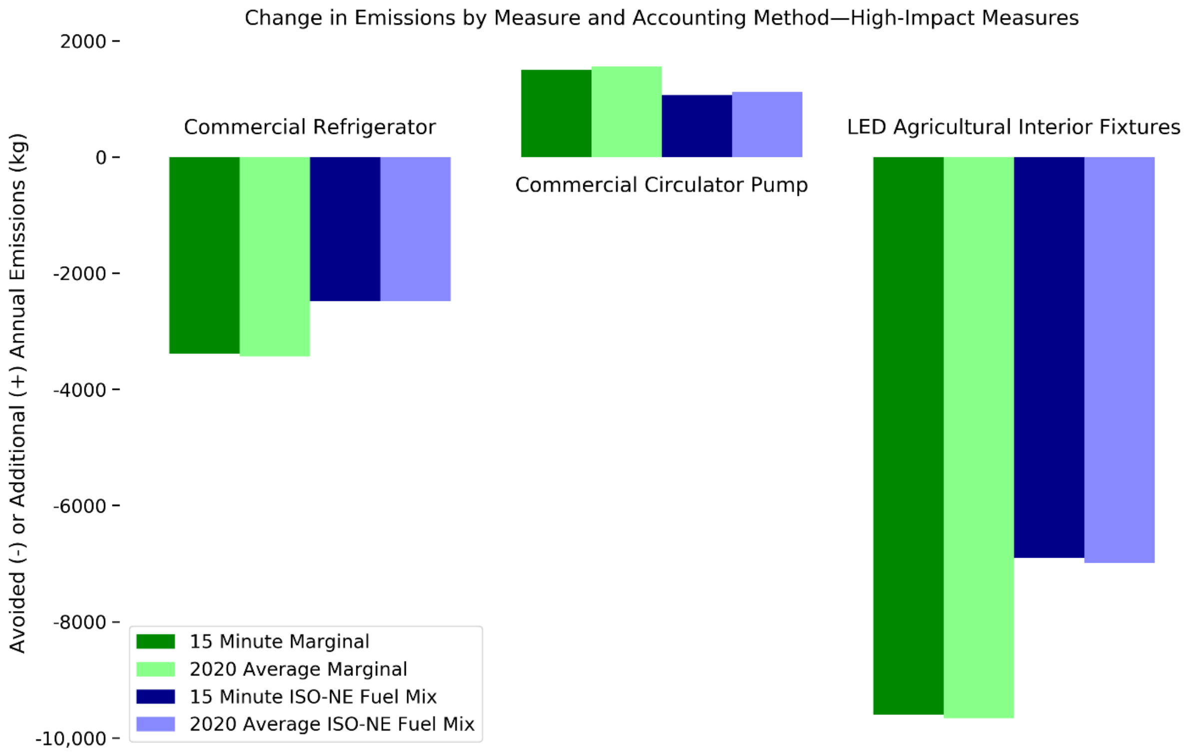


Figure 5: Change in carbon emissions by measure and accounting method—medium-impact measures

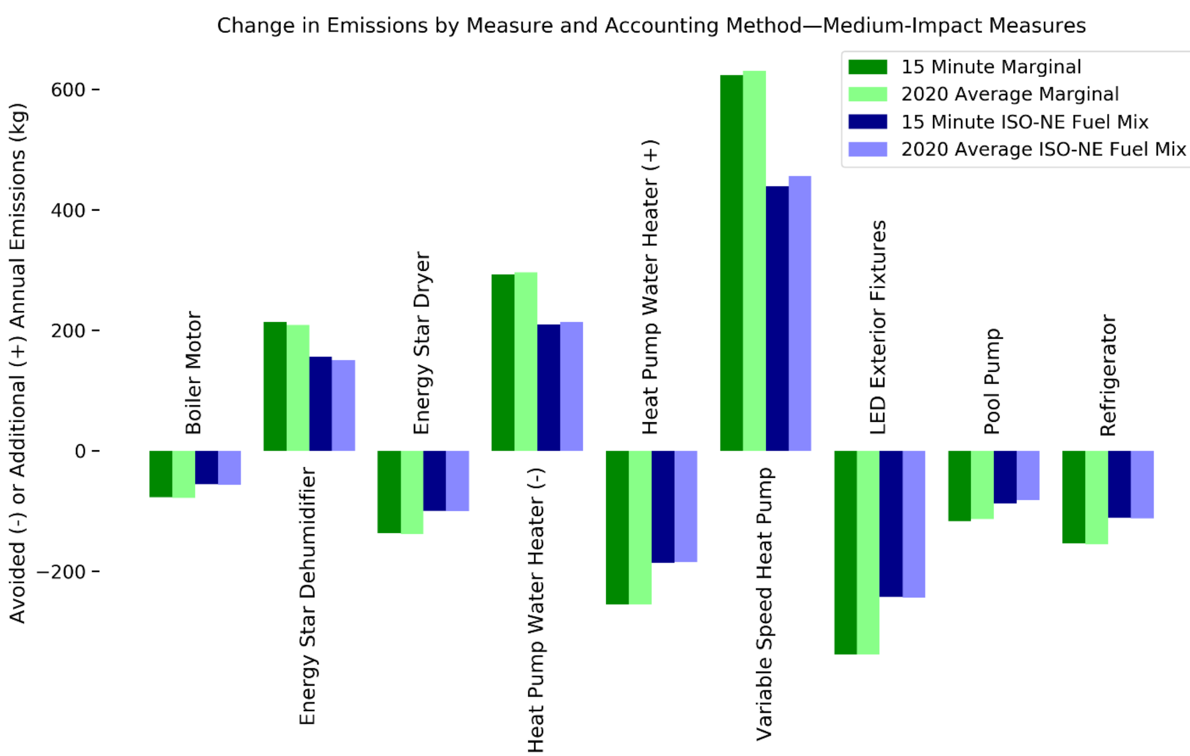
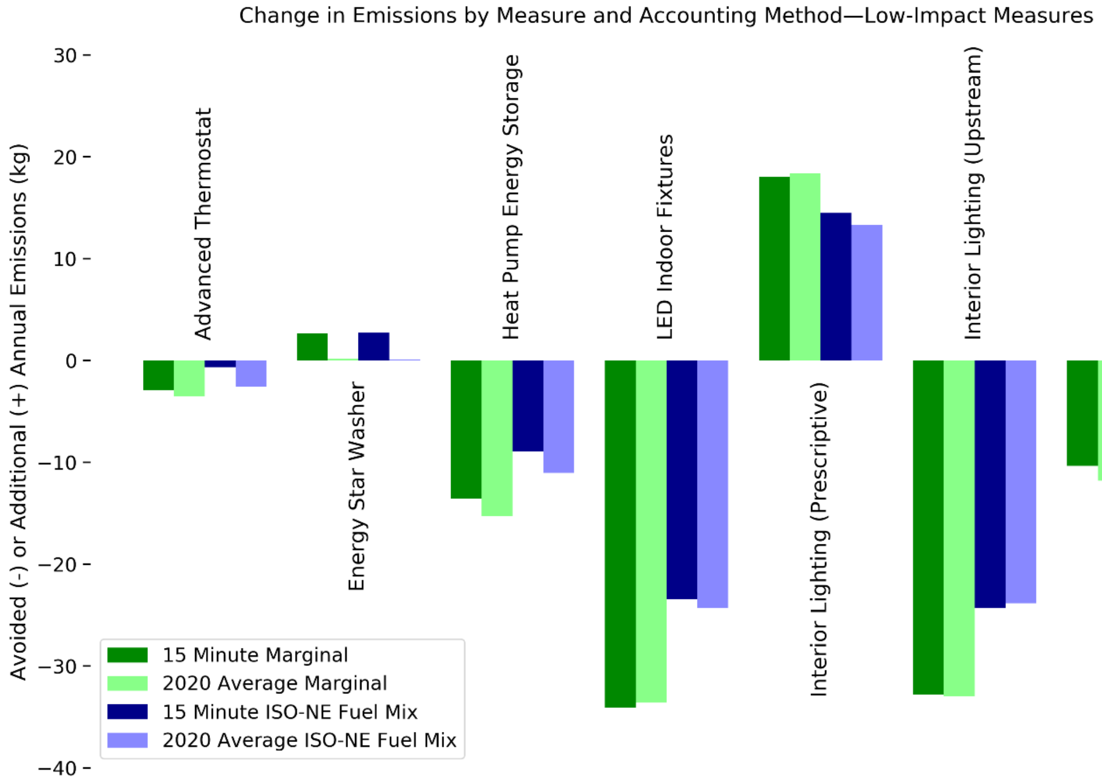


Figure 6: Change in carbon emissions by measure and accounting method—low-impact measures



The emissions savings shapes and heatmaps for all measures in this section appear in Appendix B.

MEASURE-SPECIFIC CARBON POLLUTION SHAPES

Applying ISO-NE fuel mix and emissions data to AMI data generates a description of carbon emissions pollution resulting from electricity consumption.

Heat Pumps

Figure 7 provides an example of a service point that employs a ductless mini-split heat pump. The heatmap covers three full years, 2018 through 2020. Emissions intensity at this service point is highly seasonal (intense in winters, mild in summers). The winters exhibit high time-of-day intensity variability. There is a shut-off or set-back time just before 8:00 AM and at roughly 9:00 PM. Generally, cold climate heat pumps operate at their greatest efficiency when maintaining a constant temperature rather than attempting to heat a space after prolonged setbacks; one might suggest to homeowners that they will find their living space is both more comfortable and less expensive to heat if they leave their heat pump at a single temperature setpoint.

Figure 7: Fuel mix pollution (top) and marginal fuel pollution (bottom) for GMP service point employing a ductless mini-split heat pump for heating during winter

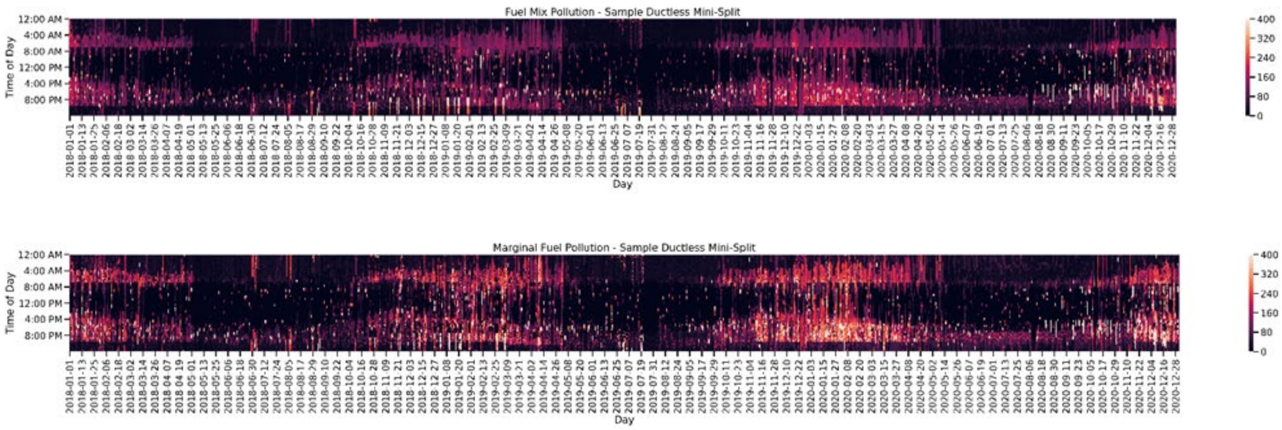
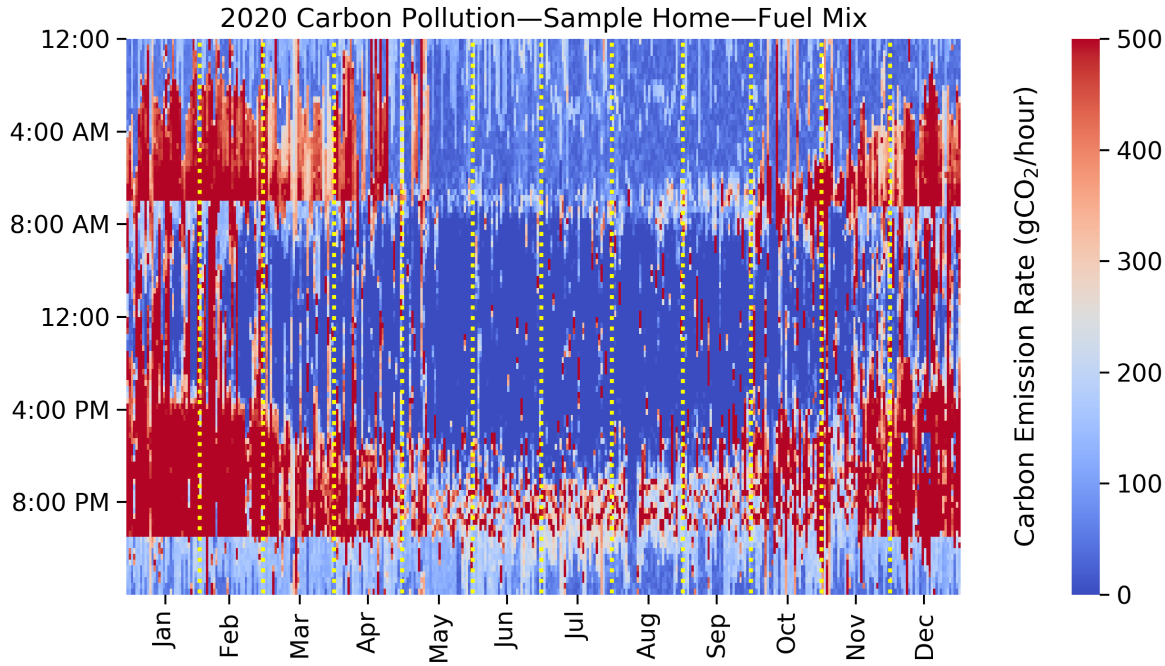


Figure 8 provides an example of a single-family home in Vermont with a cold climate heat pump. The heatmaps cover 2020. Single-family residences generally have higher balance points[7] and exemplify the outsized climate-control energy demand of Vermont winters compared with Vermont summers. This is illustrated in the red, higher-carbon emission rates during the heating season compared to the blue, lower-carbon emission rates during the cooling season on these heatmaps.

[7] The balance point, or balance temperature, is the outdoor air temperature at which the indoor temperature is optimally comfortable. It is typically between 55° and 65° F for a single-family residence. Larger buildings typically have lower balance points and therefore relatively larger cooling loads and smaller heating loads.

Figure 8: Yearlong heatmap of fuel mix (top) and marginal fuel (bottom) carbon emissions from a Vermont home with a cold climate heat pump



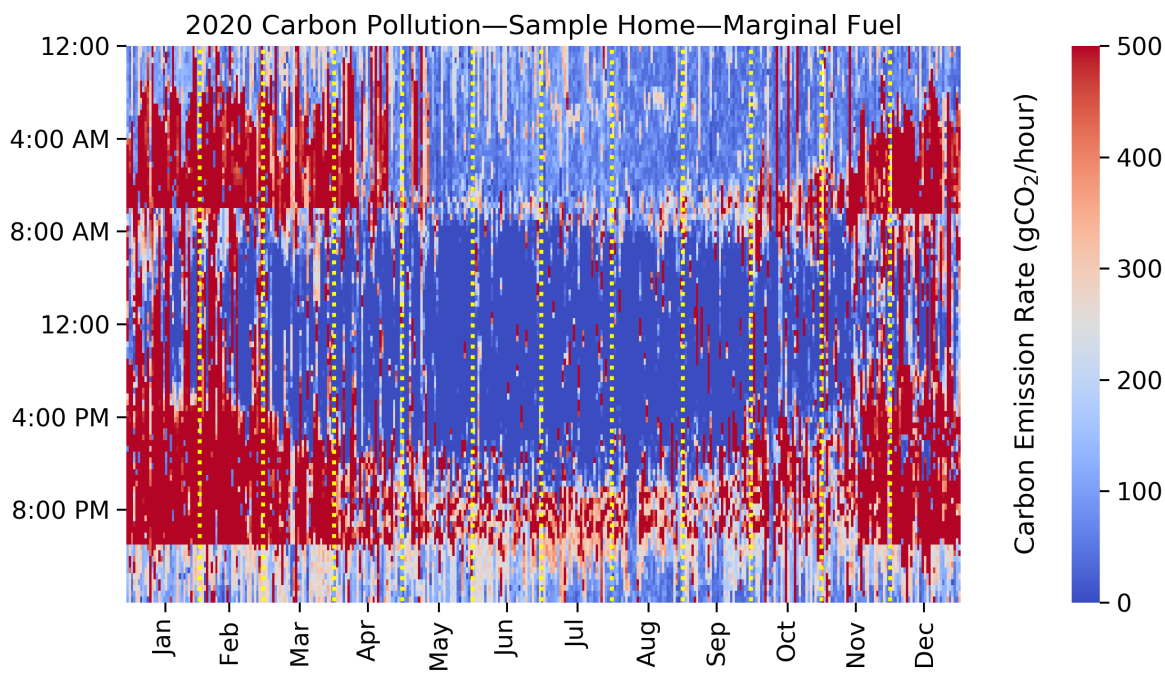
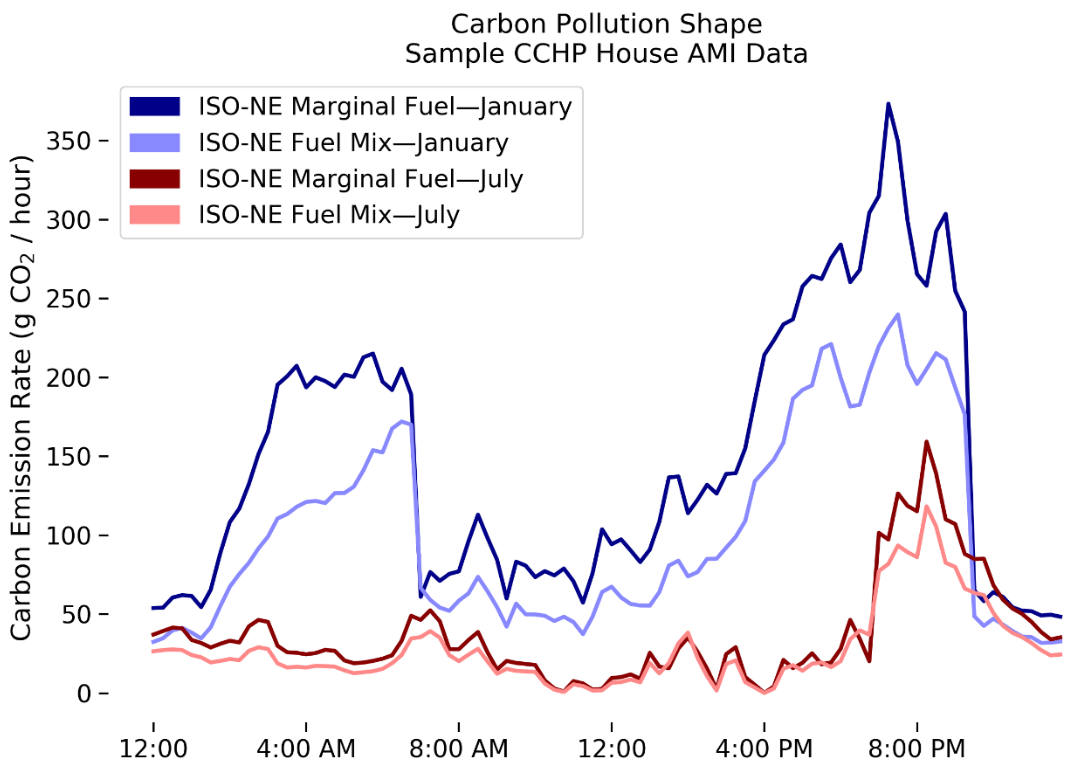


Figure 9 provides an example of pollution shapes generated using AMI data from a single-family residence with a cold climate heat pump that is used primarily in the winter. The pollution shapes represent averages from all weekdays in 2020 for the month indicated, January or July. Two trends are evident: 1) January emissions are much higher than July emissions (mostly because of increased consumption) and 2) the marginal fuel is nearly always dirtier than the overall fuel mix.

Figure 9: Carbon pollution load shapes for a single-family residence with cold climate heat pump by ISO-NE fuel mix and marginal fuel averages for January and July



These sorts of visualizations are possible to create for any individual or group (neighborhood or town) of buildings if AMI data are available. The heatmaps may be used to pinpoint times and dates when carbon pollution is heaviest and enable stakeholders to respond accordingly with demand response programs or time-of-use rates to facilitate the creation of a greener grid.

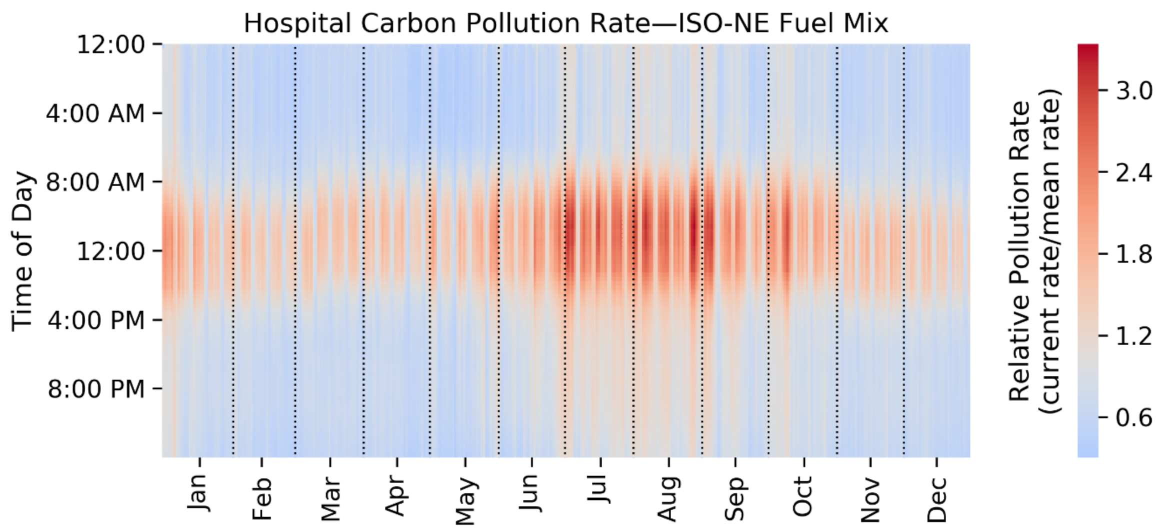
WHOLE-BUILDING CARBON POLLUTION SHAPES

In November 2021, NREL released a database of residential and commercial building load profiles for climate regions and local grids across the United States. Combining NREL's building load-shape data with ISO-NE emissions rate data creates heatmaps and average load shapes to reveal when certain types of buildings are exhibiting their most carbon intensive periods.

Hospitals

Figure 10 illustrates a New England hospital in NREL's database combined with ISO-NE fuel mix data to show relative carbon emissions rates. The red parts of this heatmap indicate times when the emissions from a hospital in the region reach a rate of roughly three times the mean. Hospitals have particularly high standards for ventilation and air quality and consequently spend enormous amounts of electricity maintaining the temperature, humidity, and low dust concentration—especially during the hot, humid summer months.

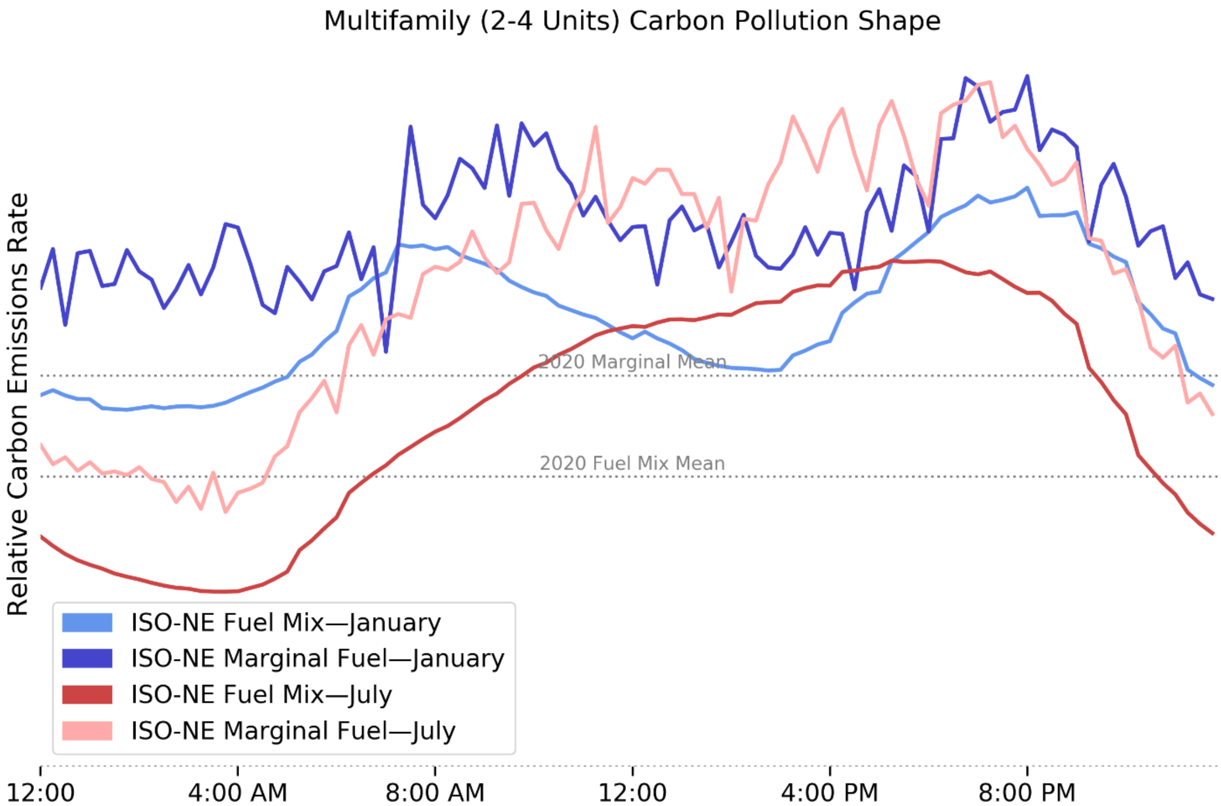
Figure 10: Hospital building type carbon pollution rate using fuel mix data



Multifamily Housing

Figure 11 graphs carbon pollution load shapes of a multifamily residential building with two to four units from the New England region in NREL's database combined with ISO-NE fuel mix and marginal data during July and January weekdays, averaged. Unlike the savings curves in the previous section, these line shapes show relative carbon intensity of the load shape rather than the savings and/or additional carbon. As with the other emissions shapes, the marginal fuel footprint is nearly always substantially higher than the corresponding fuel mix. The January fuel mix load shape looks like a residence that is vacant during the day and the July fuel mix load shape looks like a continuously occupied residence, or one where an energy intensive system, such as an air conditioner, is left on during the day.

Figure 11: Carbon pollution load shapes for a multifamily building type by ISO-NE fuel mix and marginal fuel averages for January and July.



Carbon emissions shapes largely follow the load of the building; emissions are exacerbated if the load peaks at the same time the fuel mix or marginal fuel is particularly dirty. Although customers could make peak loads less polluting by timing them for cleaner grid generation periods, there's little evidence any customers have done this in any of the representative buildings in the NREL dataset.

A selection of heatmaps and emissions shapes of a few residential buildings and commercial buildings appears in Appendix C.

Conclusion

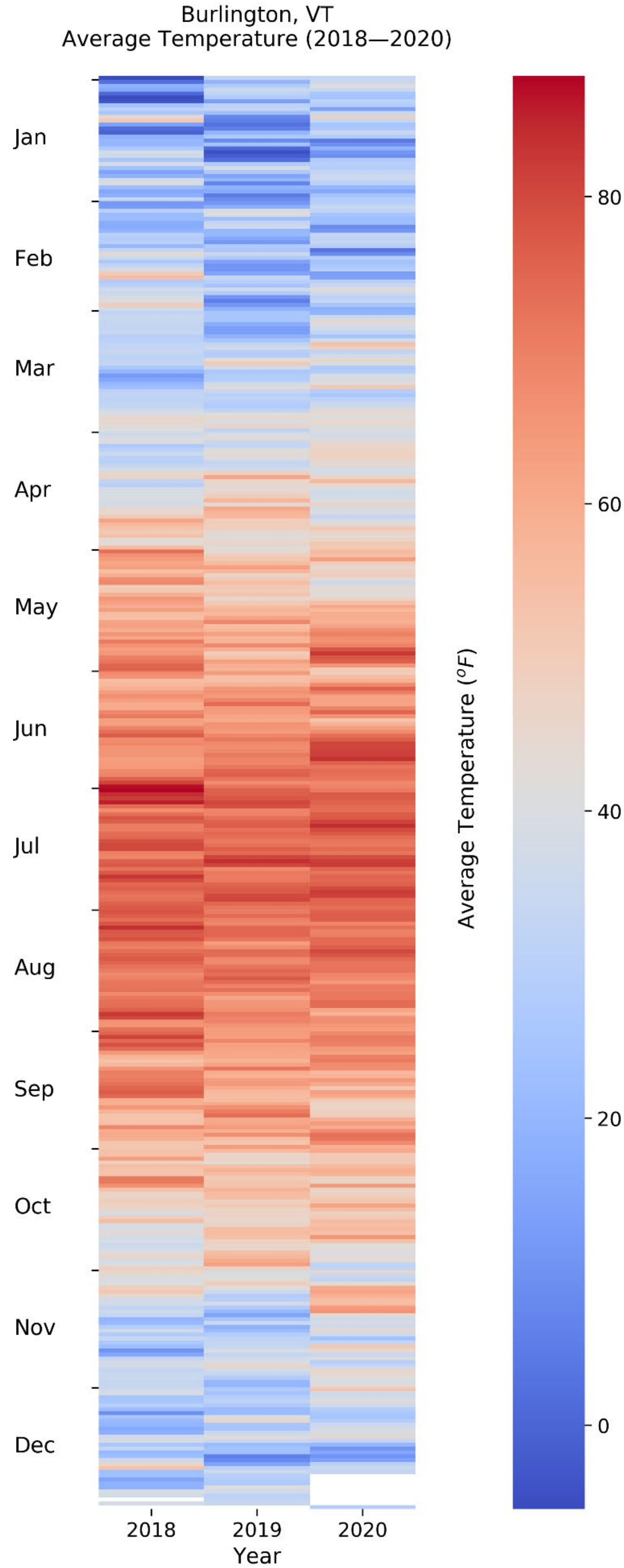
This research provides powerful visualizations of the carbon emissions impacts of electrification measures and how those measures may be best controlled to optimize grid performance and carbon savings. Carbon emissions load shapes and heatmaps can help eco-conscious customers tailor their own consumption to minimize carbon emissions. For example, informed and motivated power customers can make loads that are flexible over the span of several hours to a few days less polluting by shifting to periods when the marginal fuel is not natural gas.

Major industrial customers can make loads that are seasonally flexible less polluting by shifting them to spring and fall, when the grid fuel mix tends to be cleaner and the marginal fuel is least likely to be natural gas.

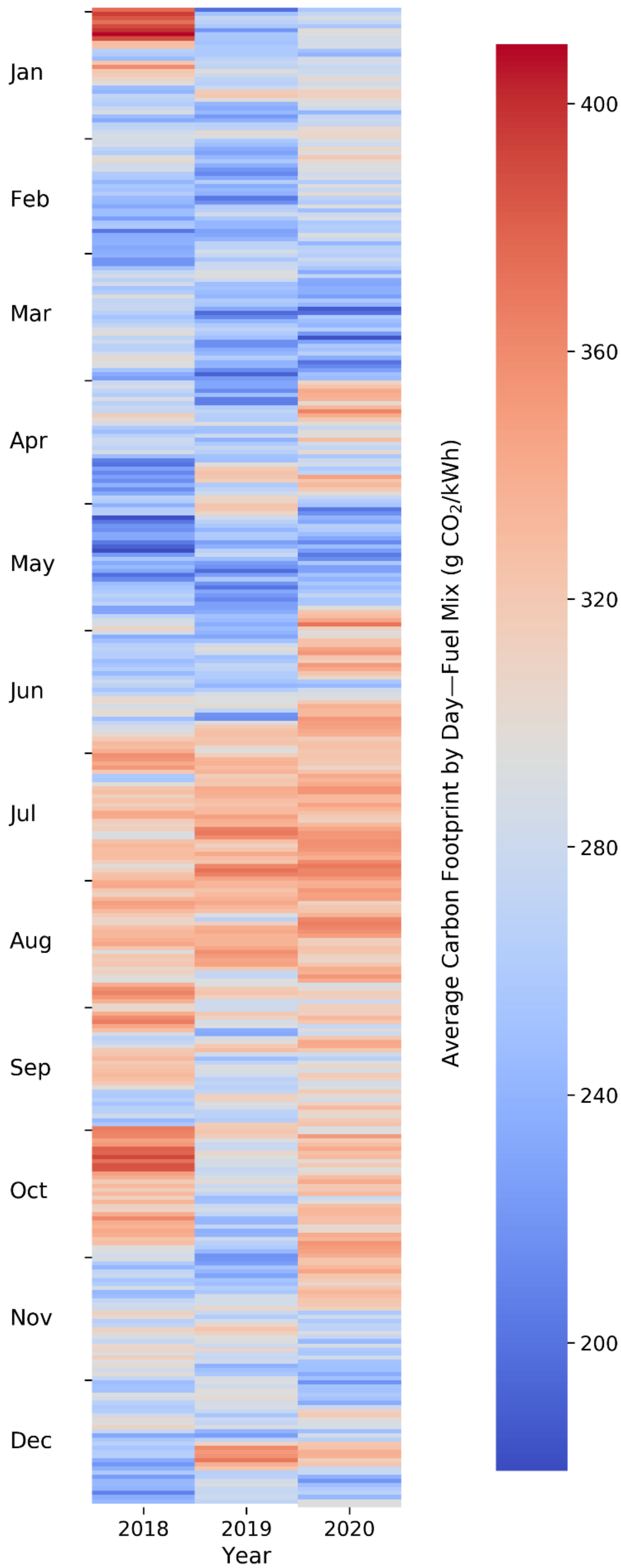
Seeing the associated carbon emissions from electrification measures enables Efficiency Vermont to optimize program designs for maximizing energy efficiency and minimizing carbon pollution. To achieve the highest accuracy pollution assessment of Vermont power customers, Efficiency Vermont needs time-resolved fuel mix and marginal fuel information from Vermont distribution utilities.

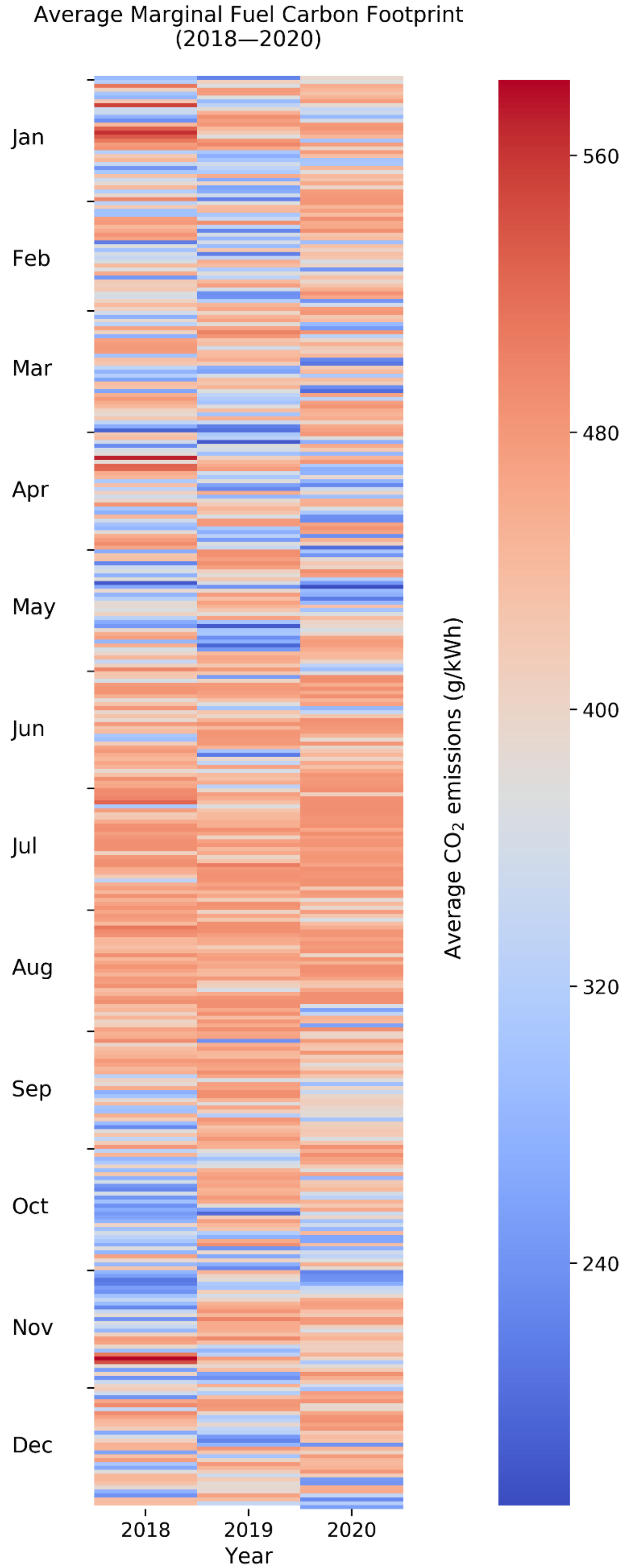
A proposed next step is to develop a self-service web-based application for creating these carbon impact visualizations on demand for portfolio-wide program design and evaluation.

Appendix A—General Grid Conditions and Temperatures (2018–2020)


Burlington, VT
Average Temperature (2018—2020)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2018
2019
2020
Year
Average Temperature (°F)
80
60
40
20
0

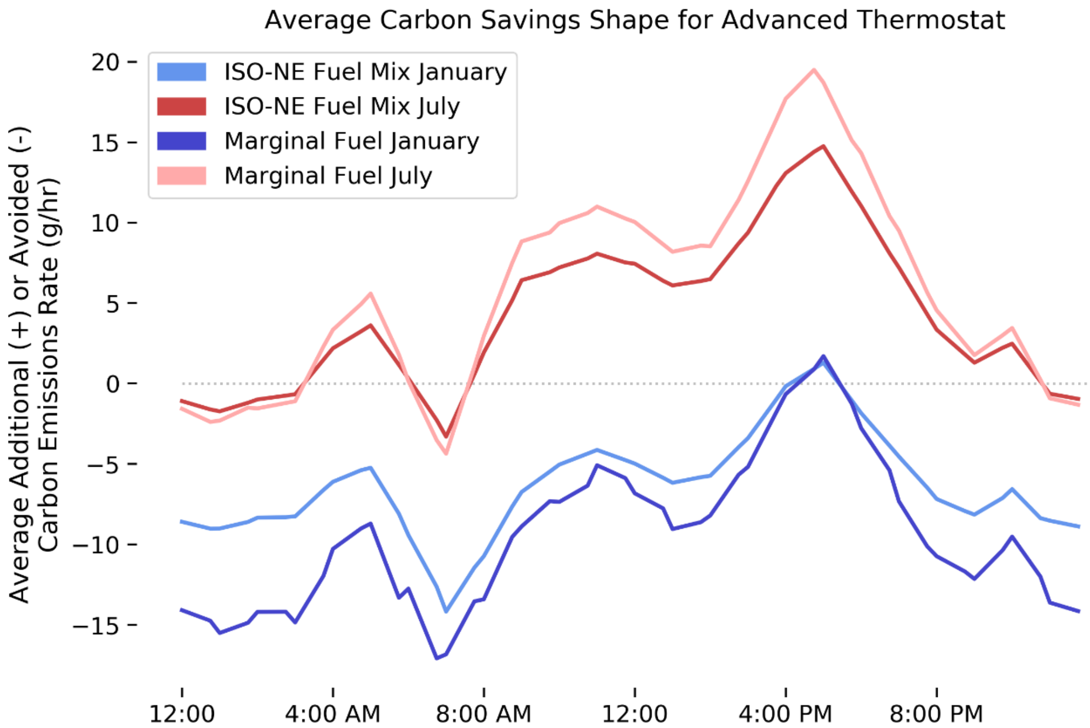
Carbon intensity—ISO-NE Fuel Mix (2018—2020)

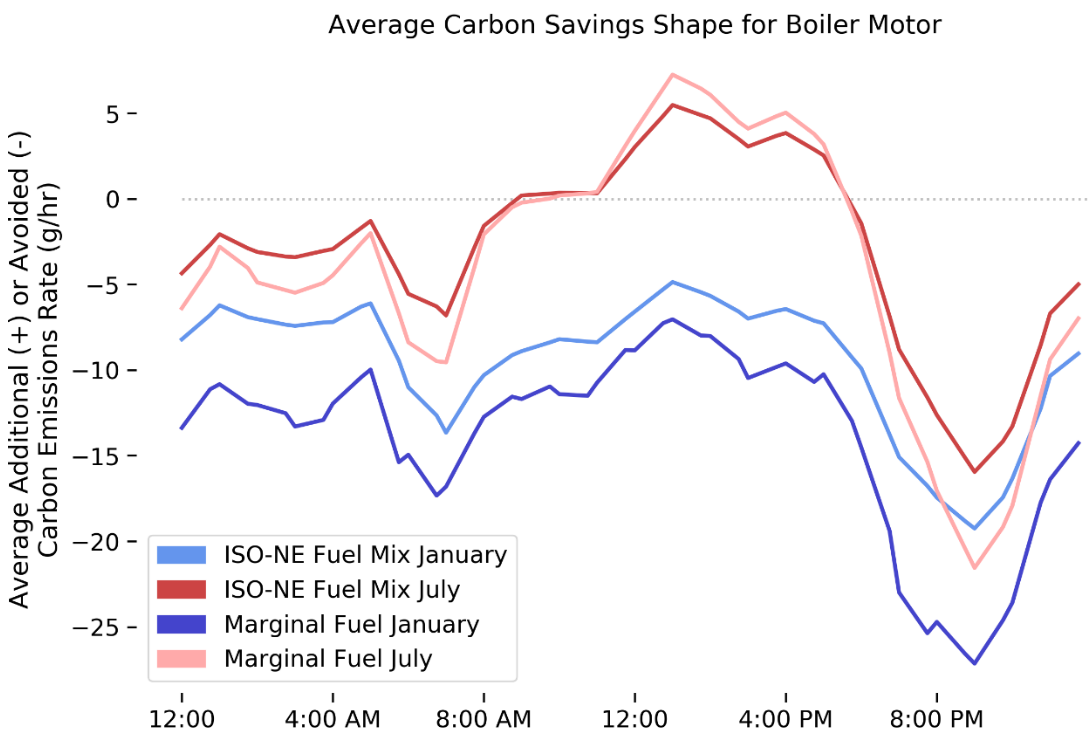



Average Marginal Fuel Carbon Footprint
(2018—2020)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2018
2019
2020
Year
Average CO_2 emissions (g/kWh)
560
480
400
320
240

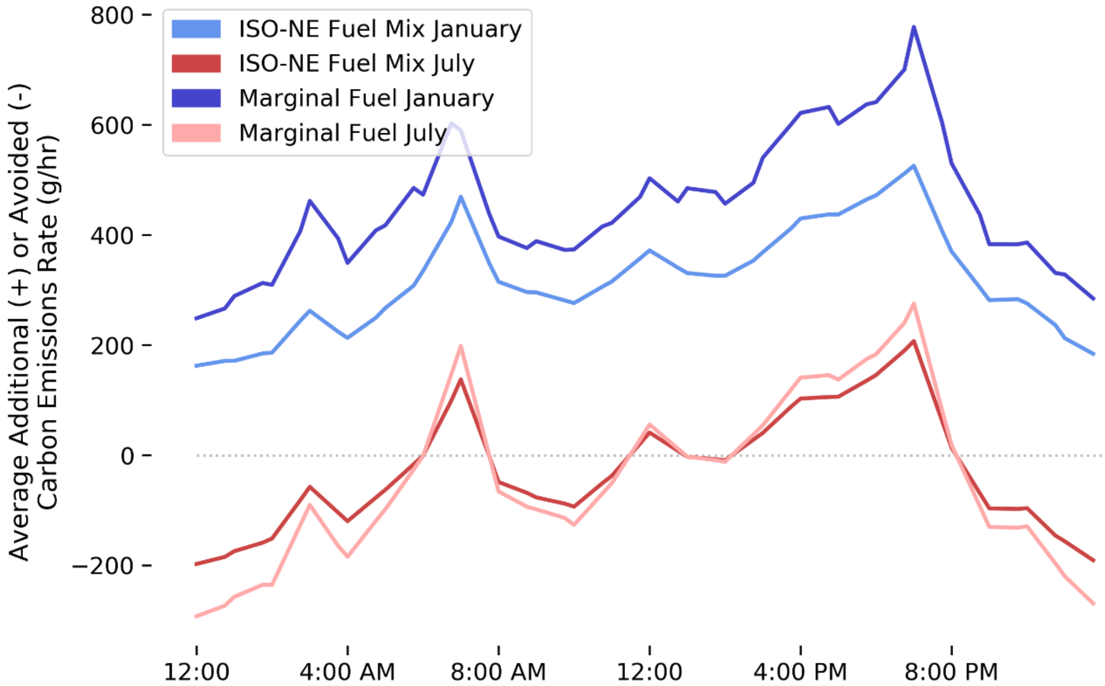
Appendix B—Emissions Savings Shapes and Heatmaps by Efficiency Measure

SAVINGS SHAPES FOR ALL EFFICIENCY MEASURES

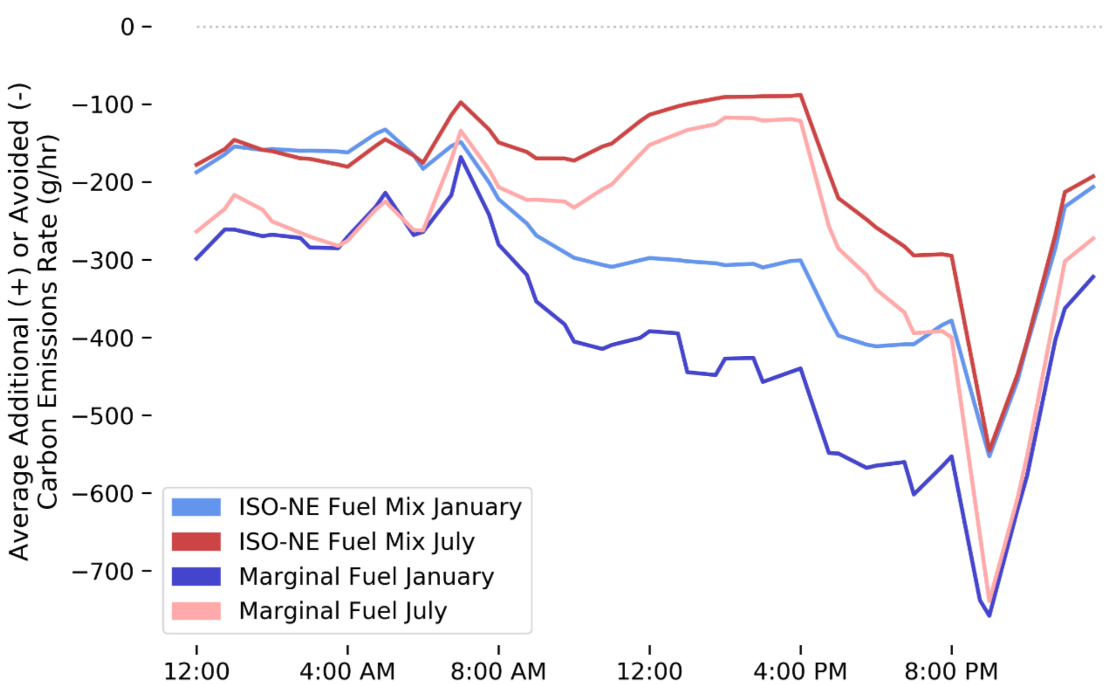

Average Carbon Savings Shape for Advanced Thermostat
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
20
15
10
5
0
−5
−10
−15
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

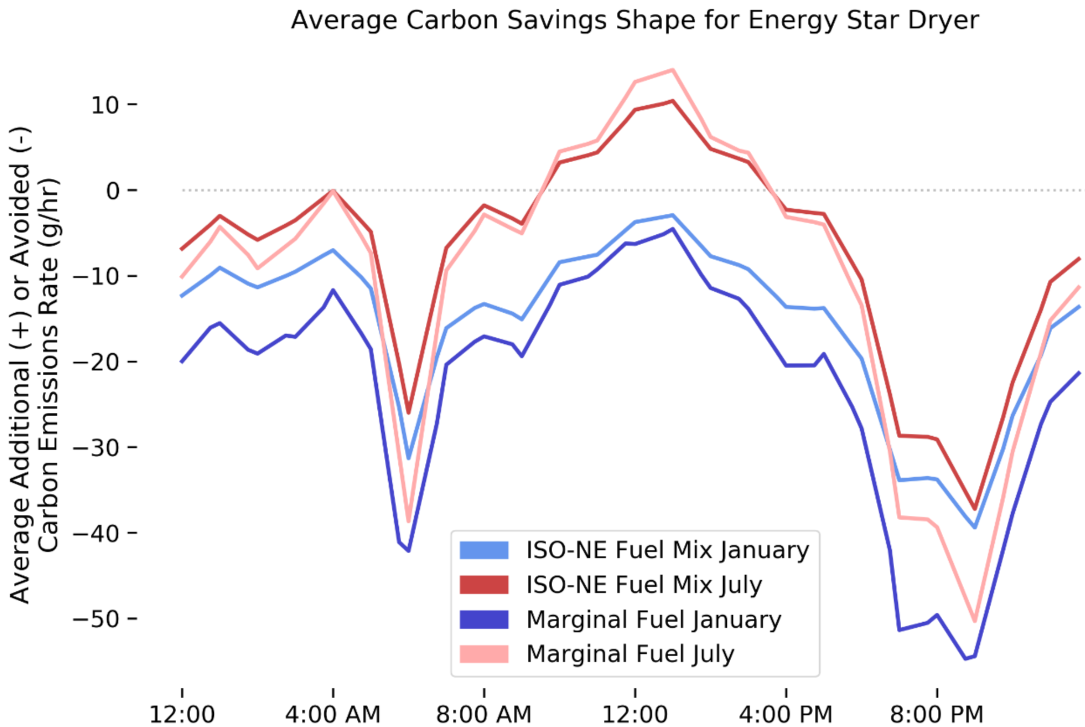

Average Carbon Savings Shape for Boiler Motor
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
5
0
−5
−10
−15
−20
−25
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

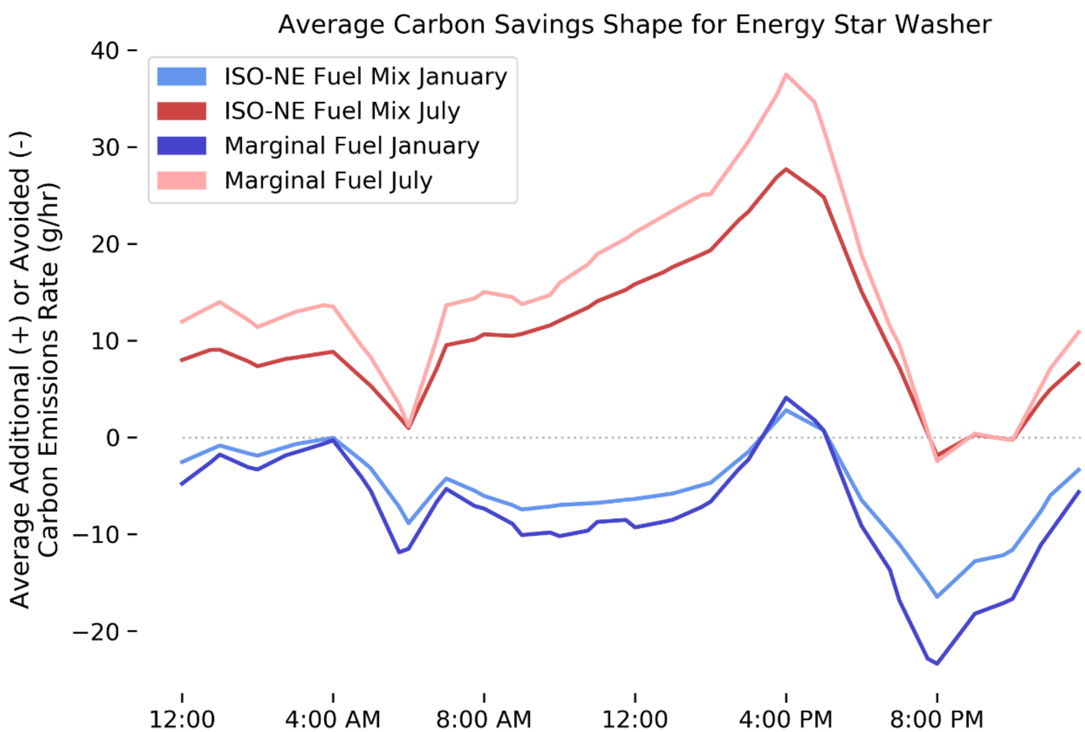
Average Carbon Savings Shape for Commercial Circulator Pump

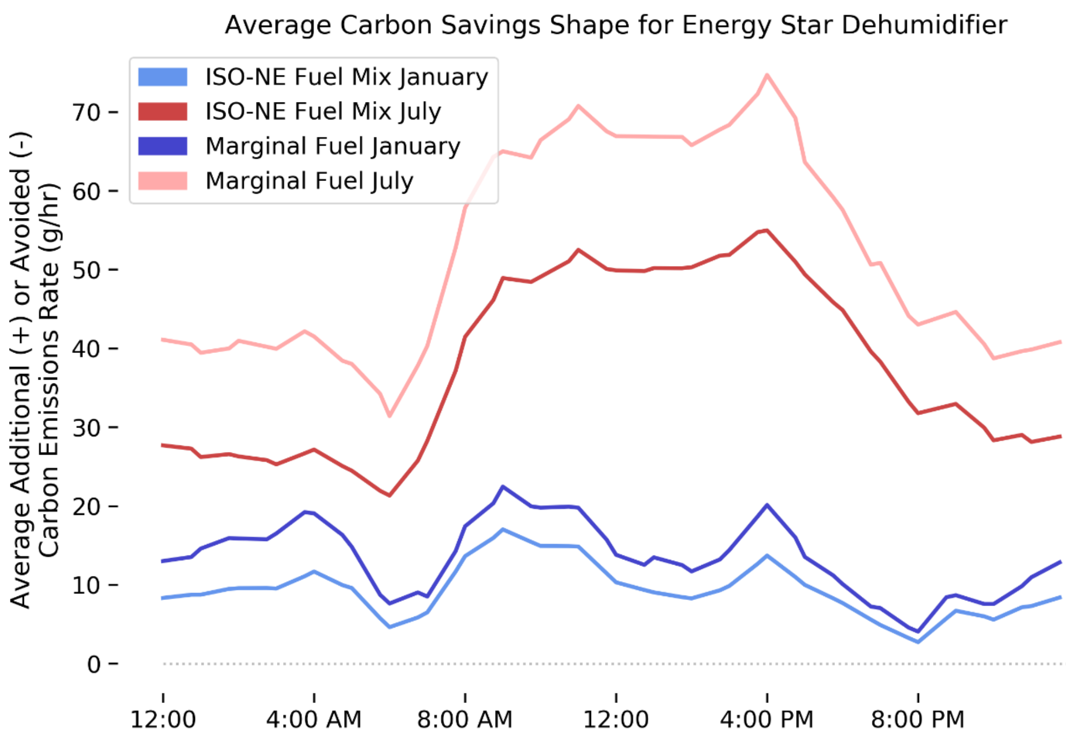


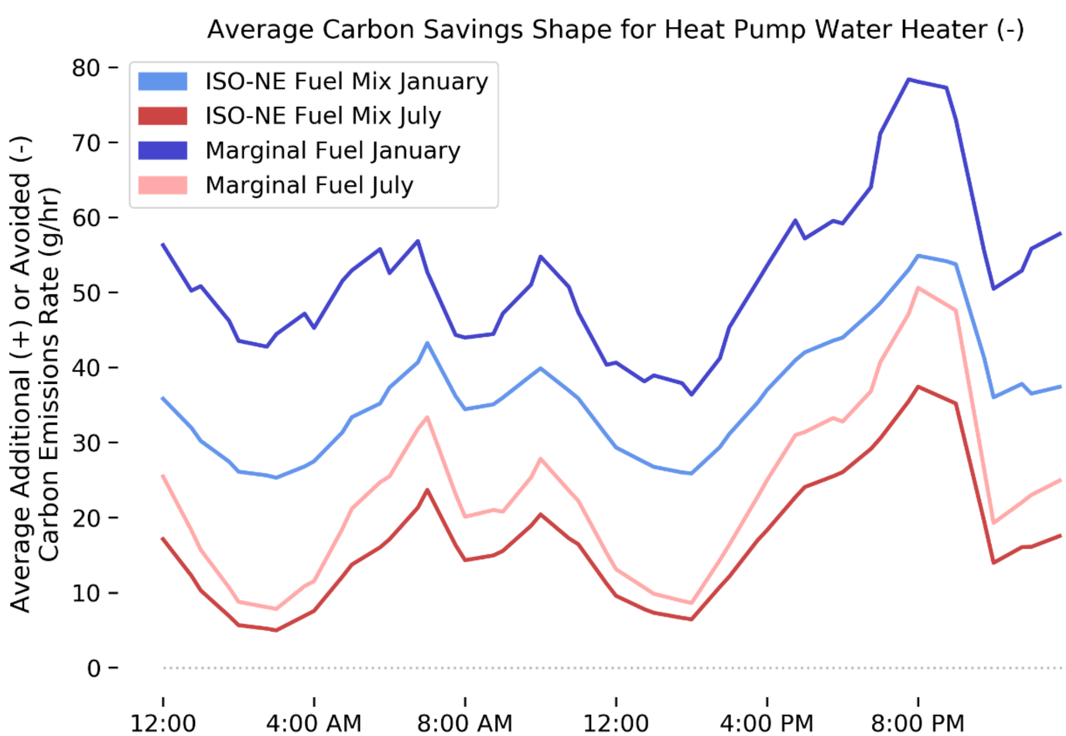
Average Carbon Savings Shape for Commercial Refrigerator

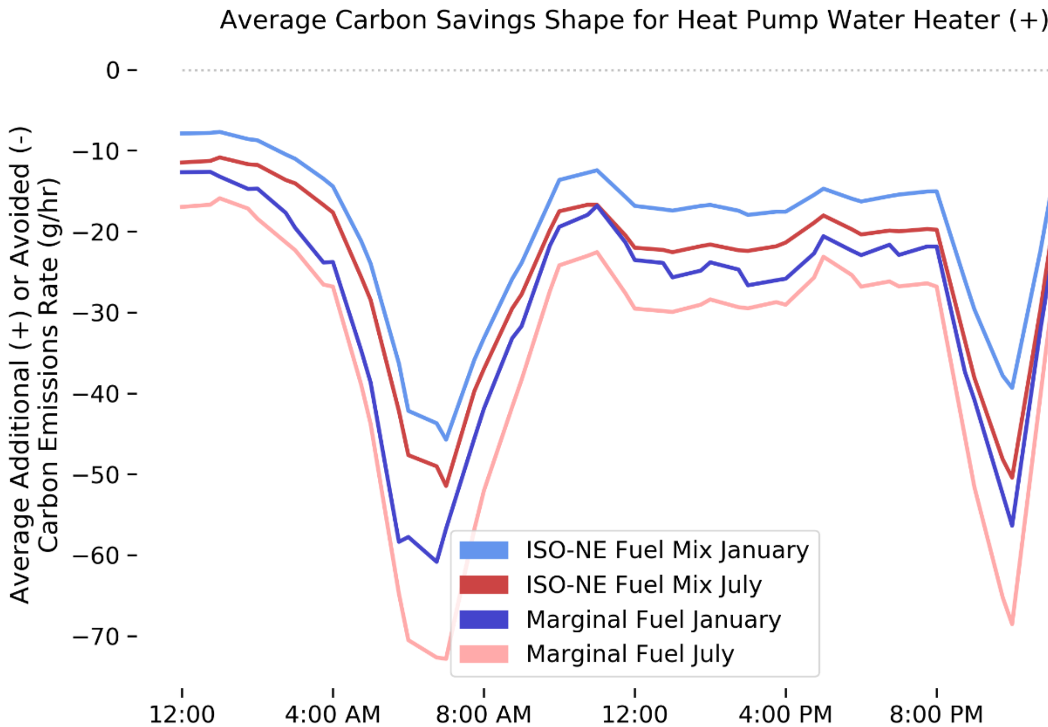


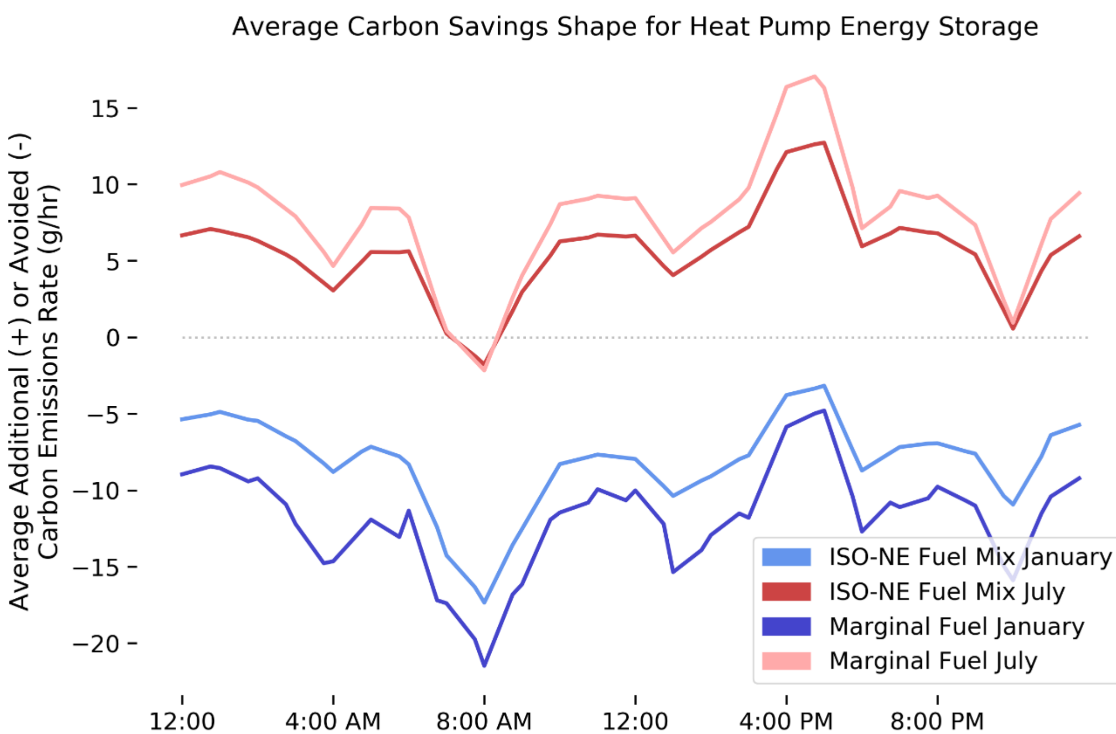

Average Carbon Savings Shape for Energy Star Dryer
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
10
0
−10
−20
−30
−40
−50
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

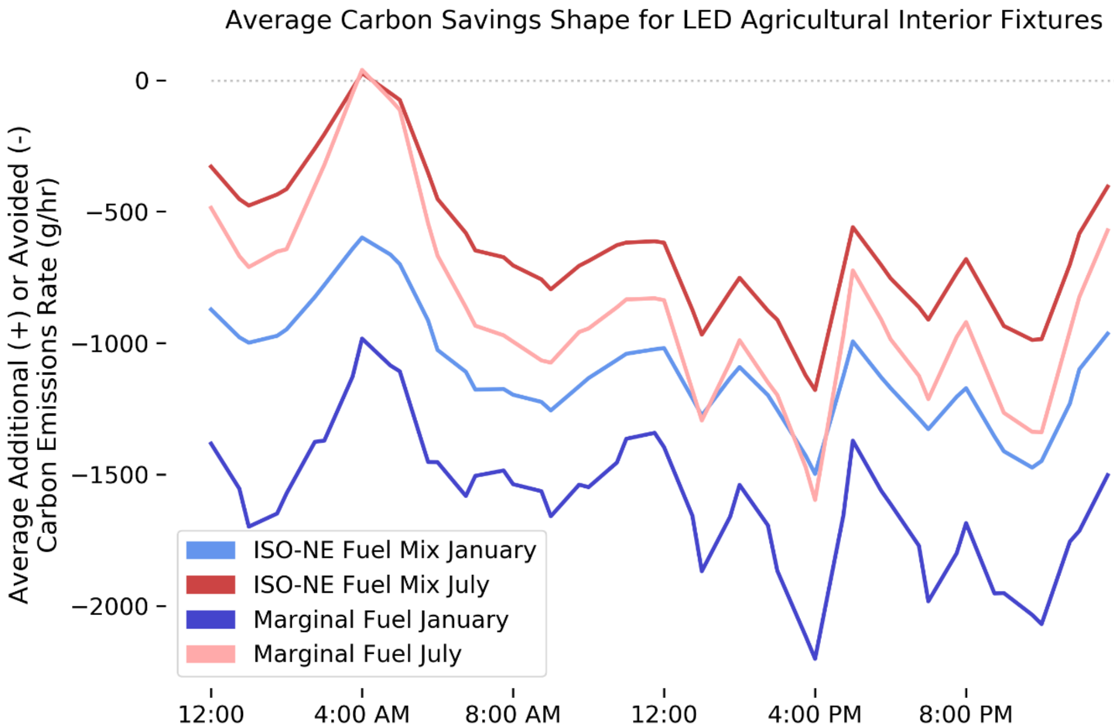

Average Carbon Savings Shape for Energy Star Washer
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
40
30
20
10
0
−10
−20
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

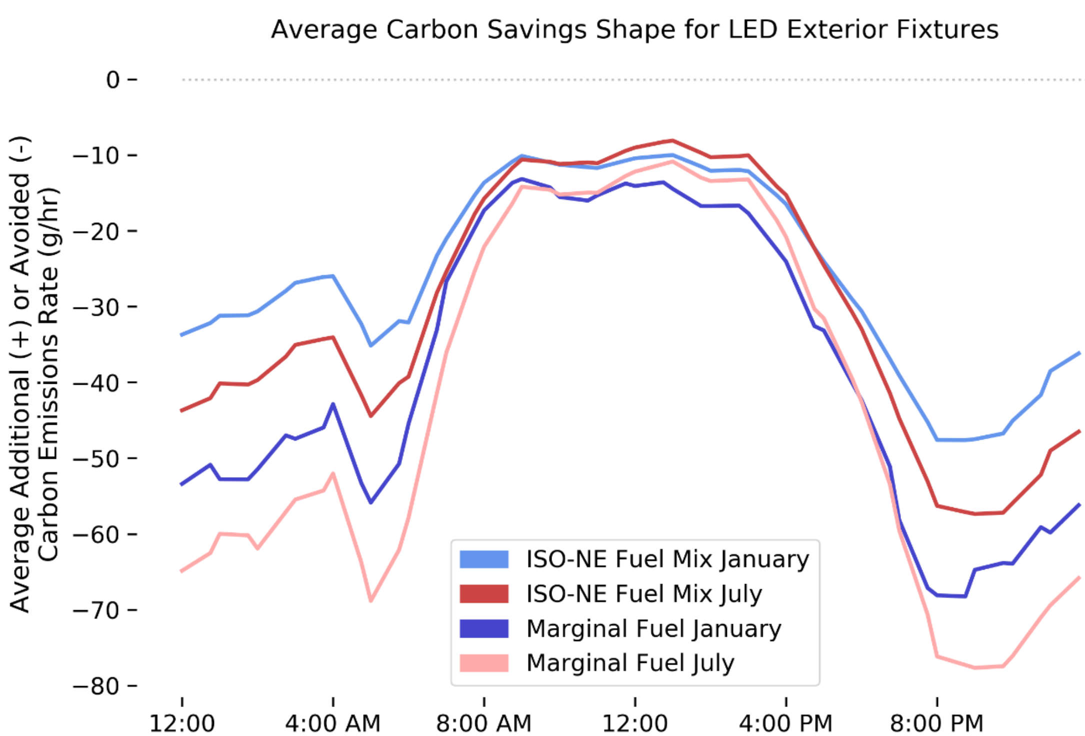

Average Carbon Savings Shape for Energy Star Dehumidifier
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
0
10
20
30
40
50
60
70
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

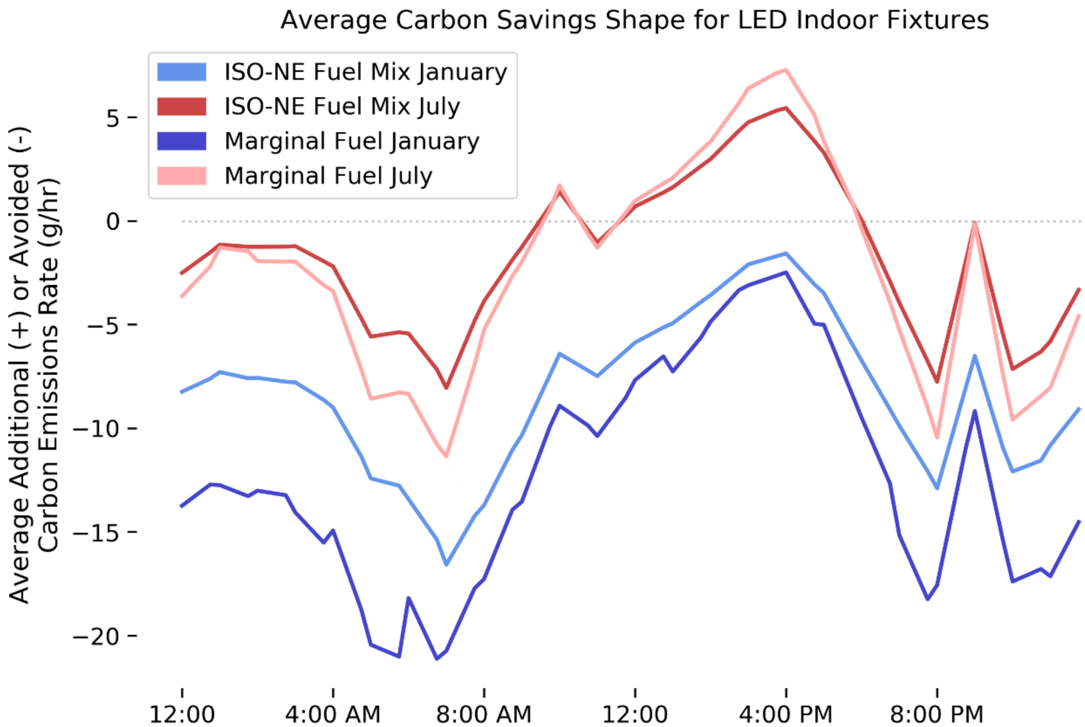

Average Carbon Savings Shape for Heat Pump Water Heater (-)
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
0
10
20
30
40
50
60
70
80
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

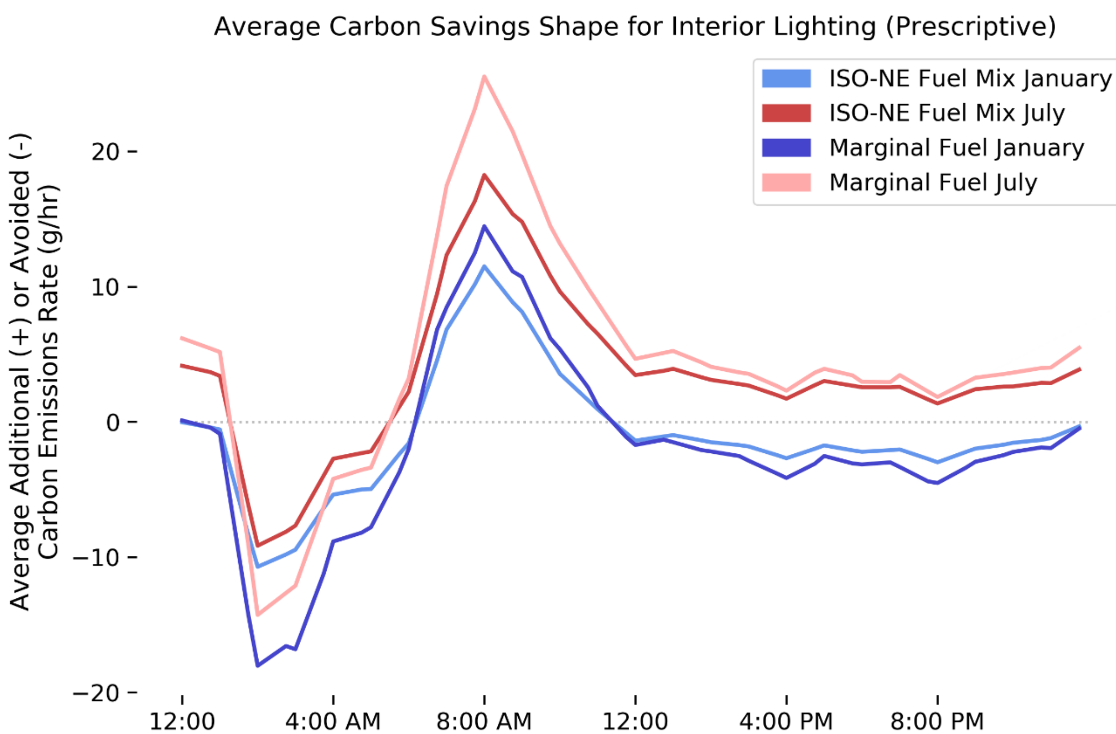

Average Carbon Savings Shape for Heat Pump Water Heater (+)
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
0
−10
−20
−30
−40
−50
−60
−70
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

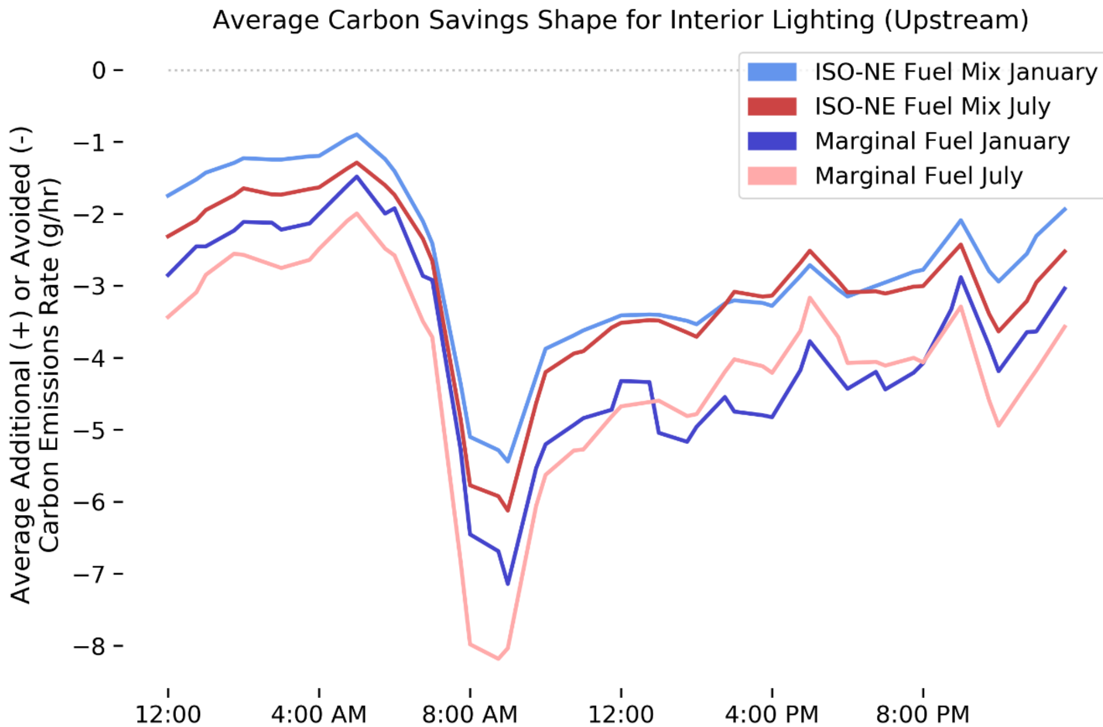

Average Carbon Savings Shape for Heat Pump Energy Storage
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
15
10
5
0
−5
−10
−15
−20
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

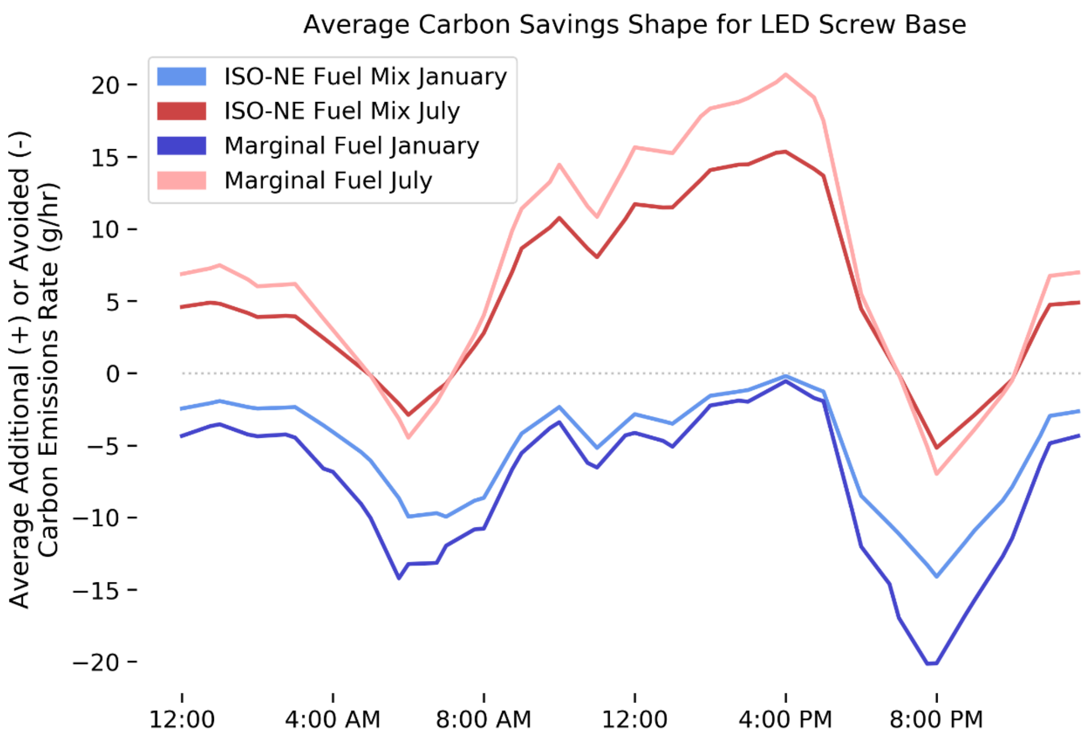

Average Carbon Savings Shape for LED Agricultural Interior Fixtures
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
0
−500
−1000
−1500
−2000
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

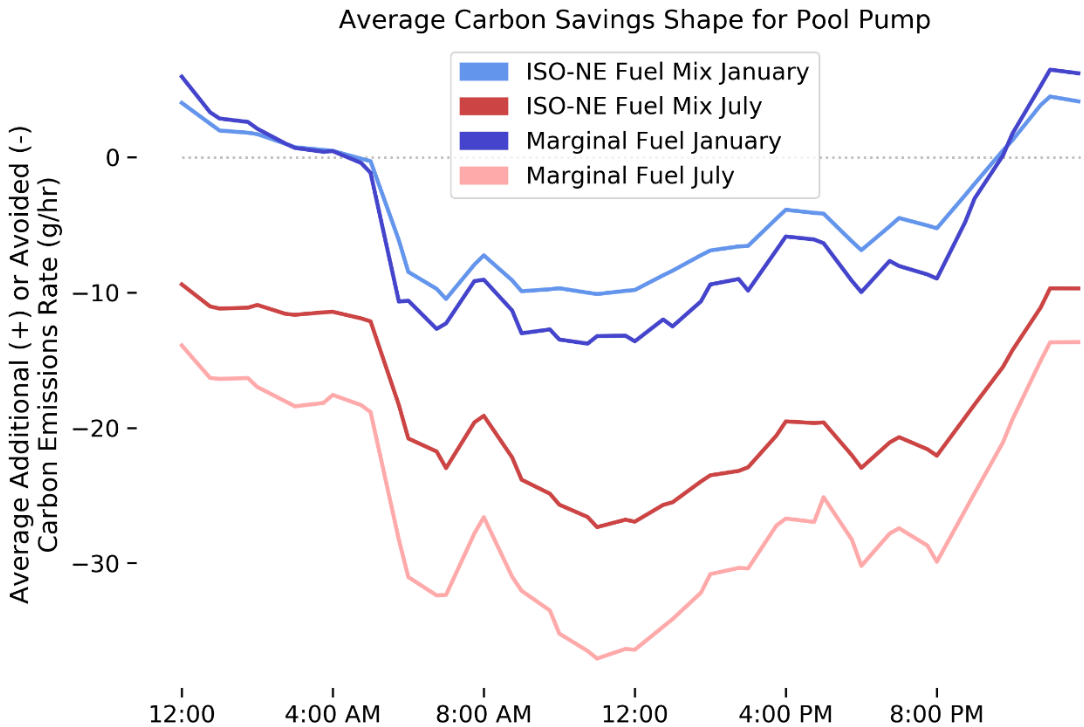

Average Carbon Savings Shape for LED Exterior Fixtures
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
0
−10
−20
−30
−40
−50
−60
−70
−80
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

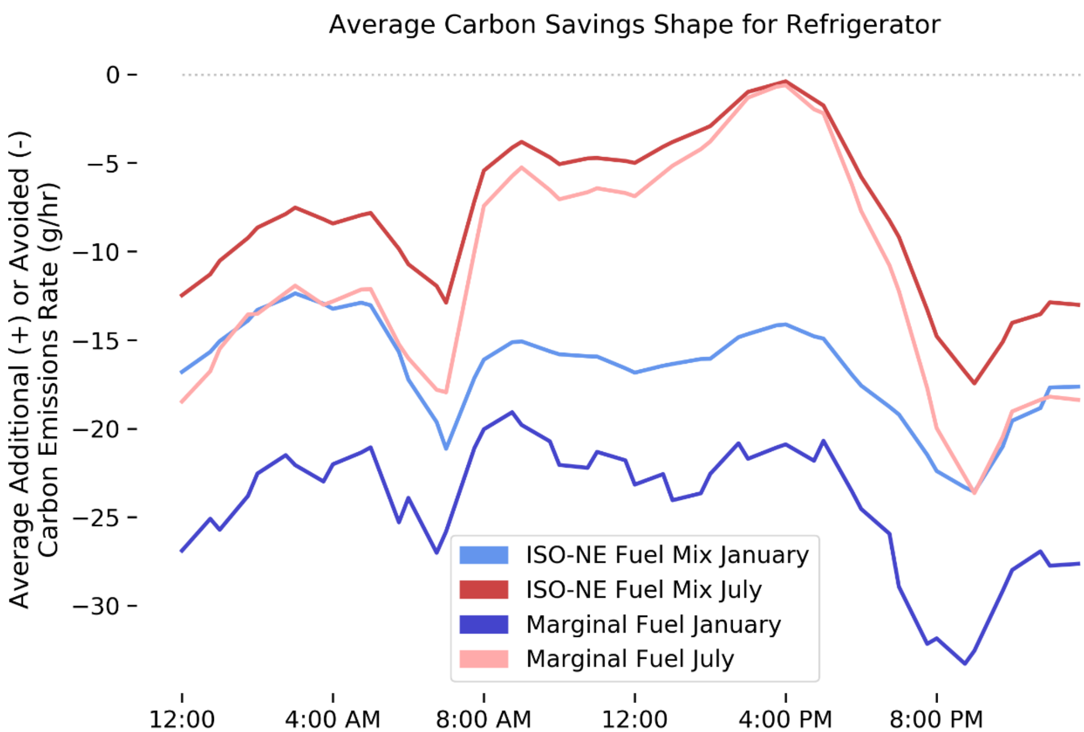

Average Carbon Savings Shape for LED Indoor Fixtures
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
5
0
−5
−10
−15
−20
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

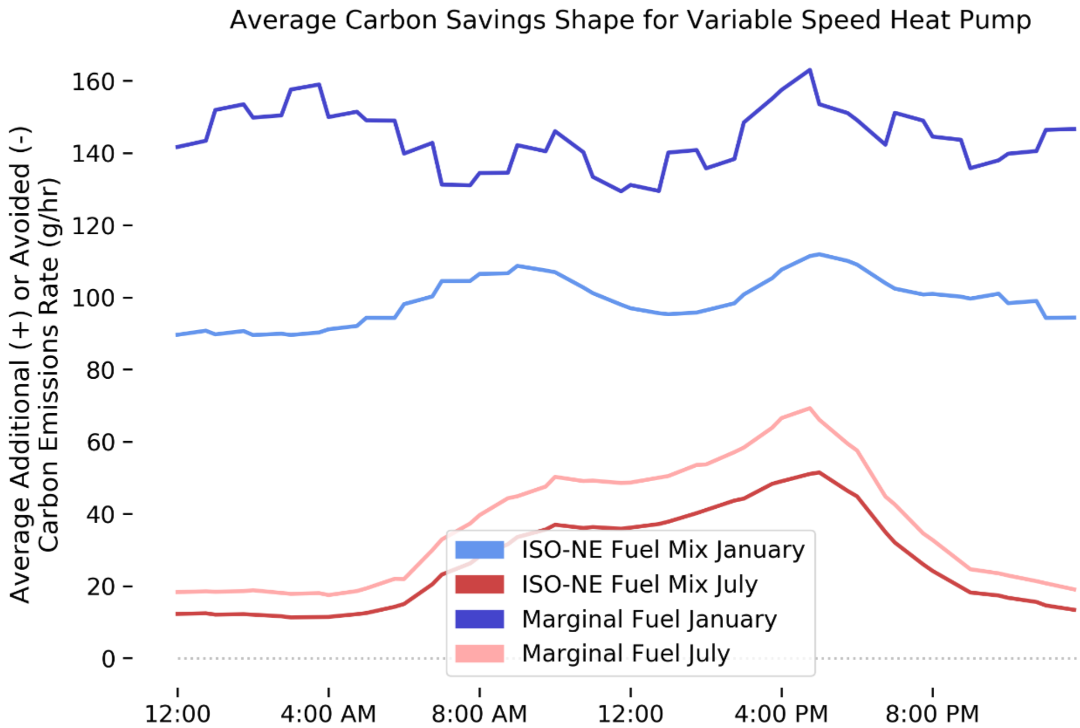

Average Carbon Savings Shape for Interior Lighting (Prescriptive)
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
20
10
0
−10
−20
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM


Average Carbon Savings Shape for Interior Lighting (Upstream)
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
0
−1
−2
−3
−4
−5
−6
−7
−8
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

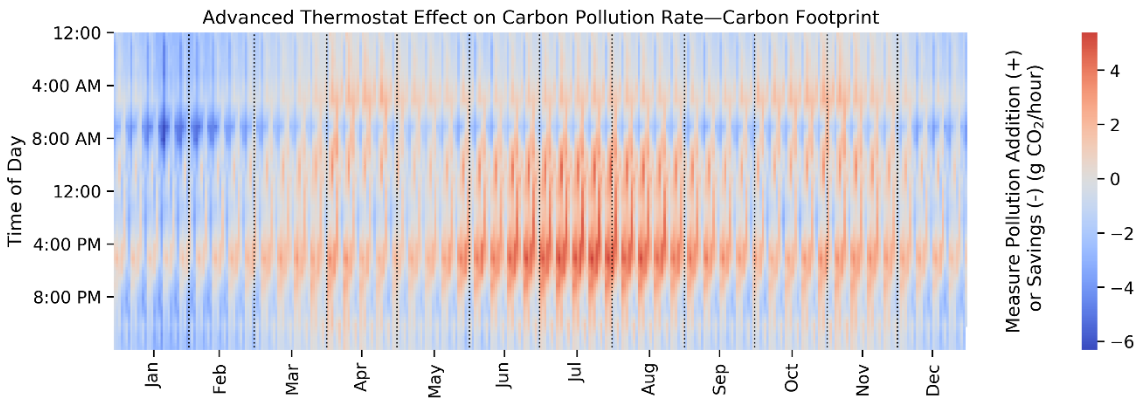

Average Carbon Savings Shape for LED Screw Base
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
20
15
10
5
0
−5
−10
−15
−20
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

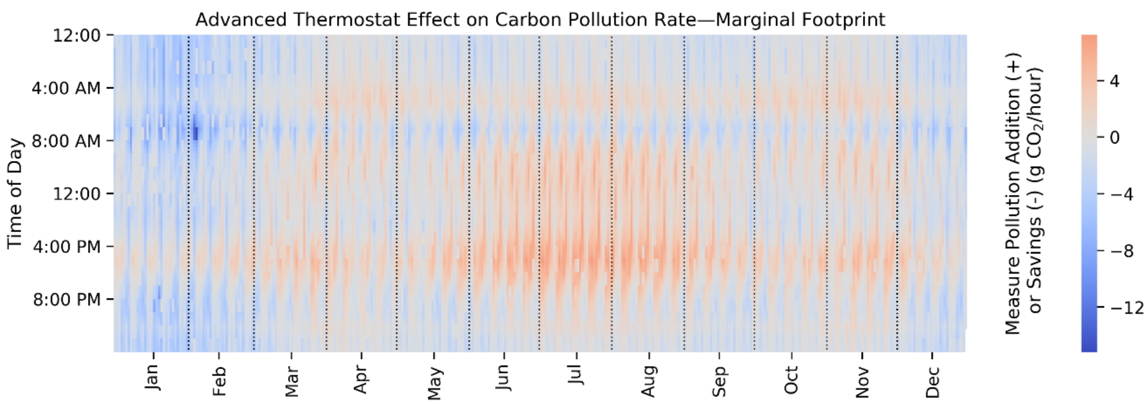

Average Carbon Savings Shape for Pool Pump
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
0
−10
−20
−30
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

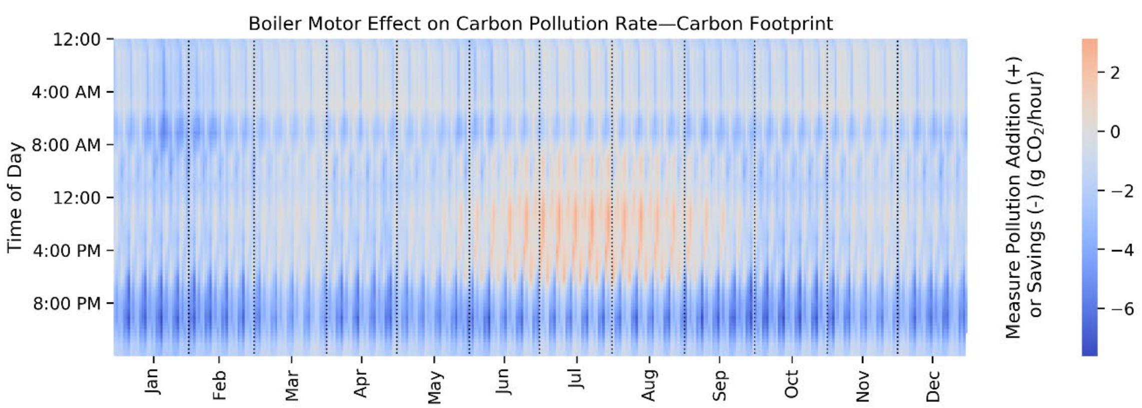

Average Carbon Savings Shape for Refrigerator
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
0
−5
−10
−15
−20
−25
−30
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

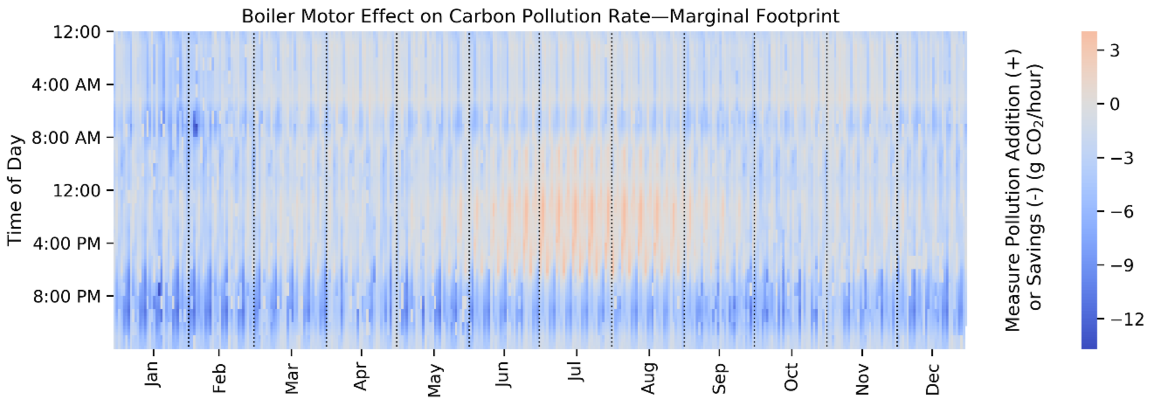

Average Carbon Savings Shape for Variable Speed Heat Pump
Average Additional (+) or Avoided (-) Carbon Emissions Rate (g/hr)
160
140
120
100
80
60
40
20
0
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
ISO-NE Fuel Mix January
ISO-NE Fuel Mix July
Marginal Fuel January
Marginal Fuel July

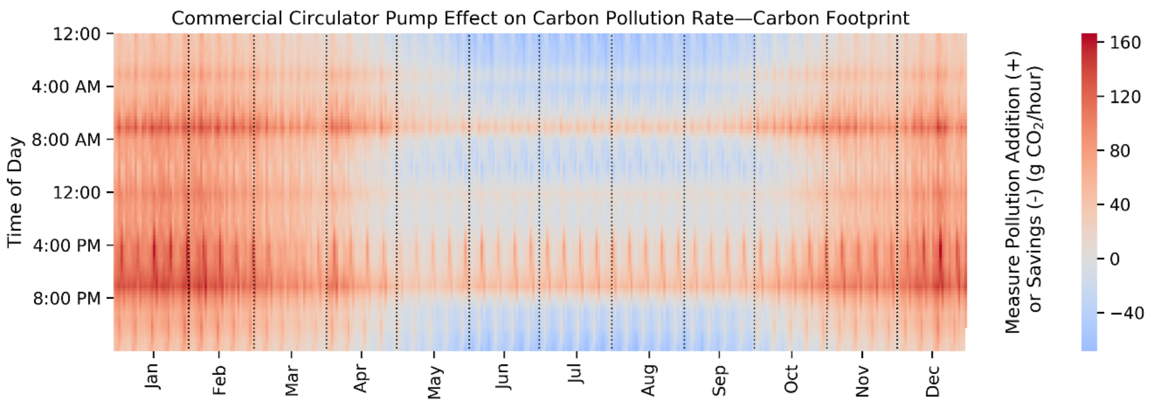
HEATMAPS FOR CARBON EMISSIONS SAVINGS / ADDITIONS BY EFFICIENCY MEASURE

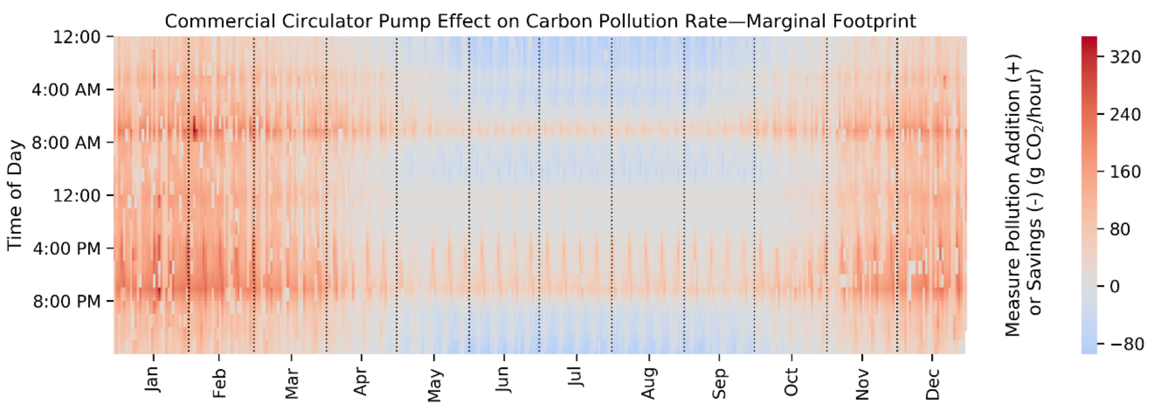


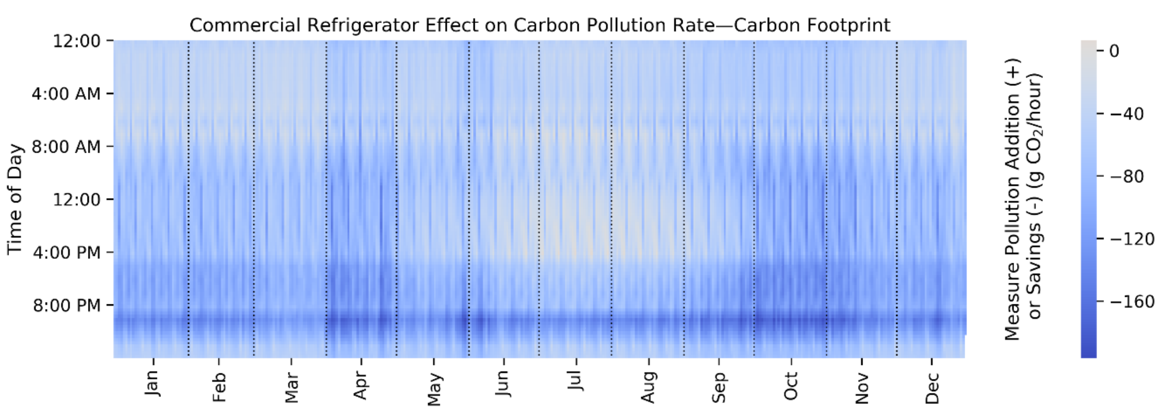


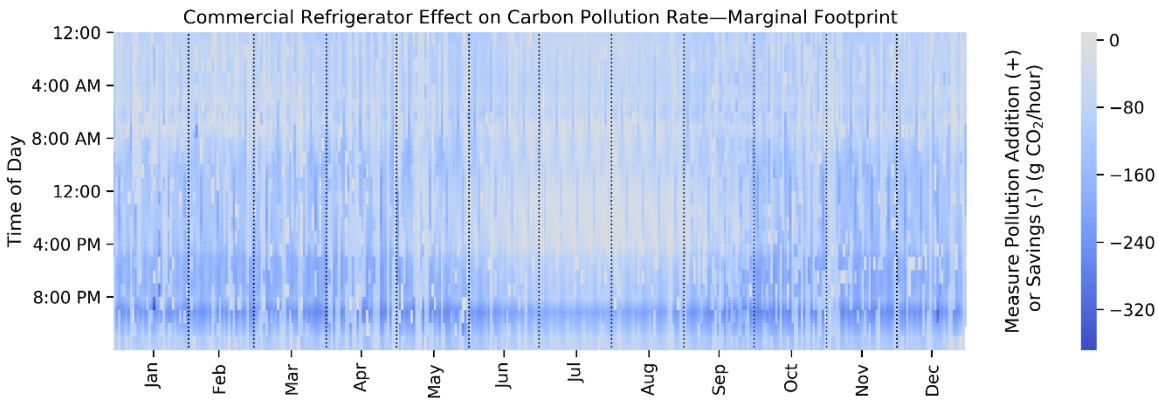



Boiler Motor Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
3
0
−3
−6
−9
−12

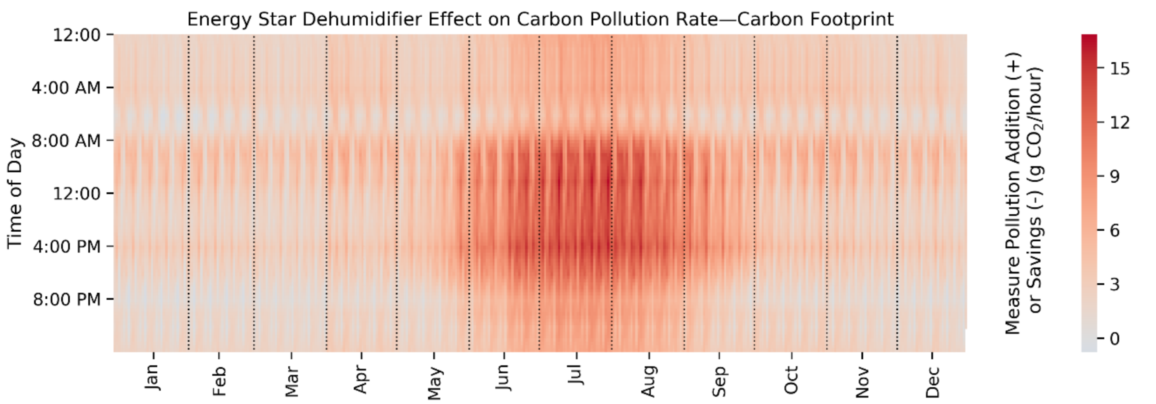

Commercial Circulator Pump Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
160
120
80
40
0
−40


Commercial Circulator Pump Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
320
240
160
80
0
−80

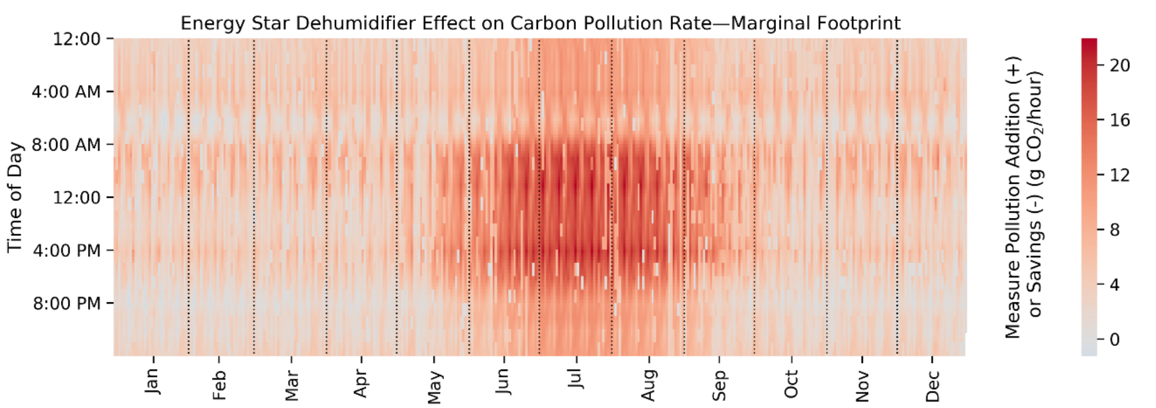

Commercial Refrigerator Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
0
−40
−80
−120
−160



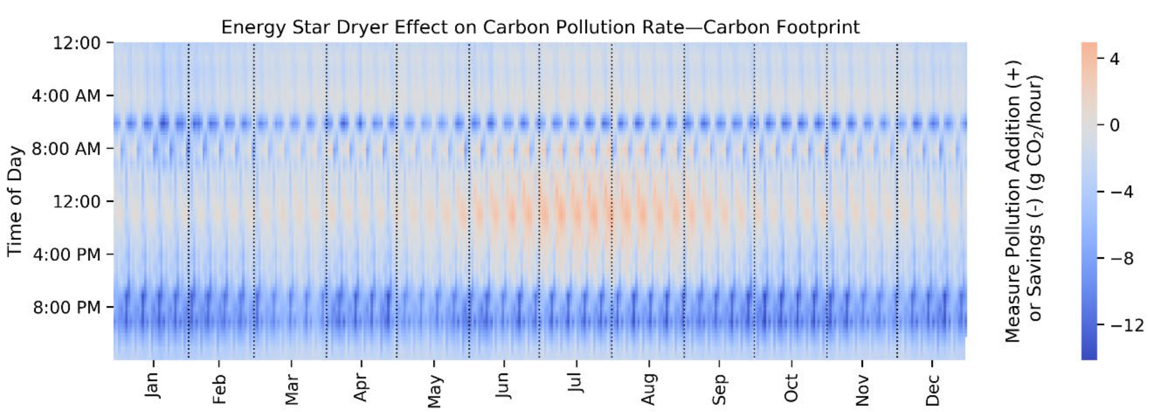
Commercial Refrigerator Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO2/hour)
0
−80
−160
−240
−320



Energy Star Dehumidifier Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO2/hour)
15
12
9
6
3
0

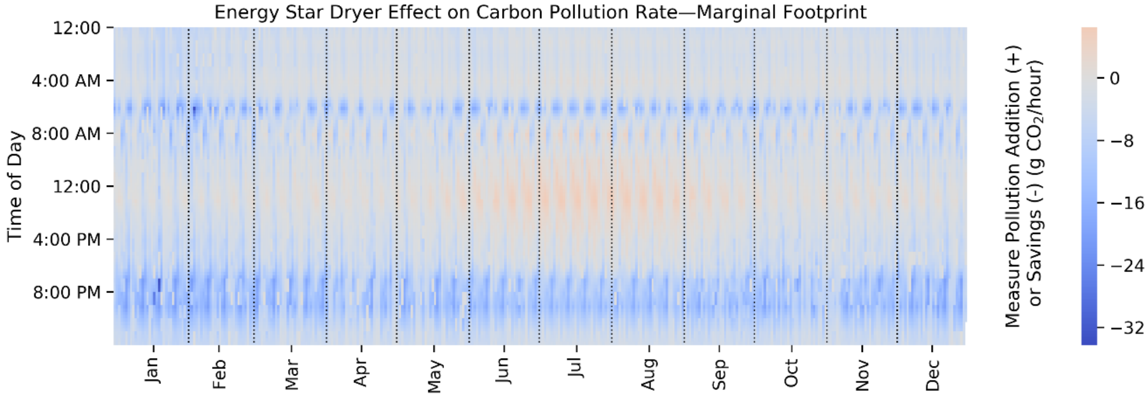


Energy Star Dehumidifier Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO2/hour)
20
16
12
8
4
0

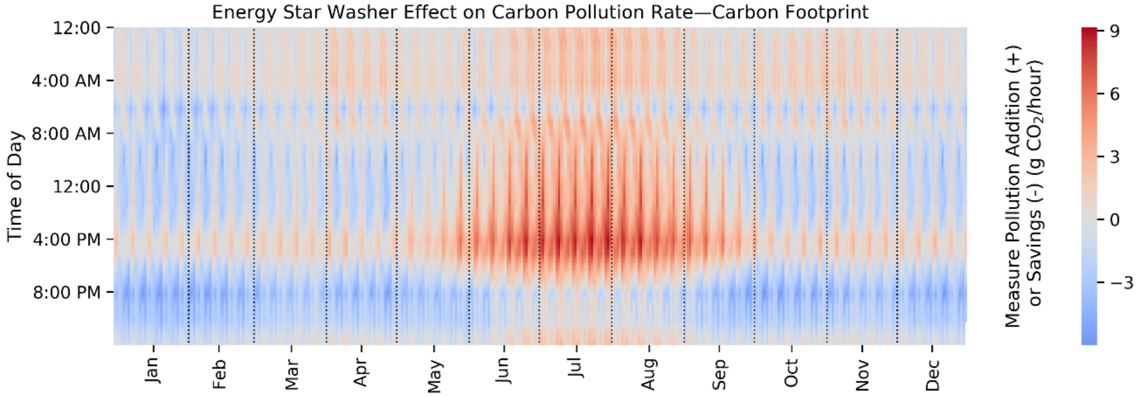


Energy Star Dryer Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO2/hour)
4
0
−4
−8
−12

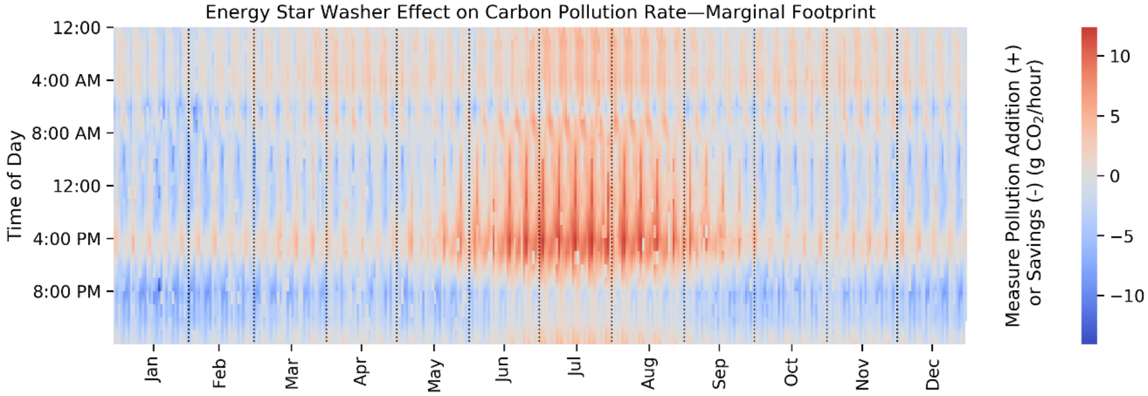
Energy Star Dryer Effect on Carbon Pollution Rate—Marginal Footprint



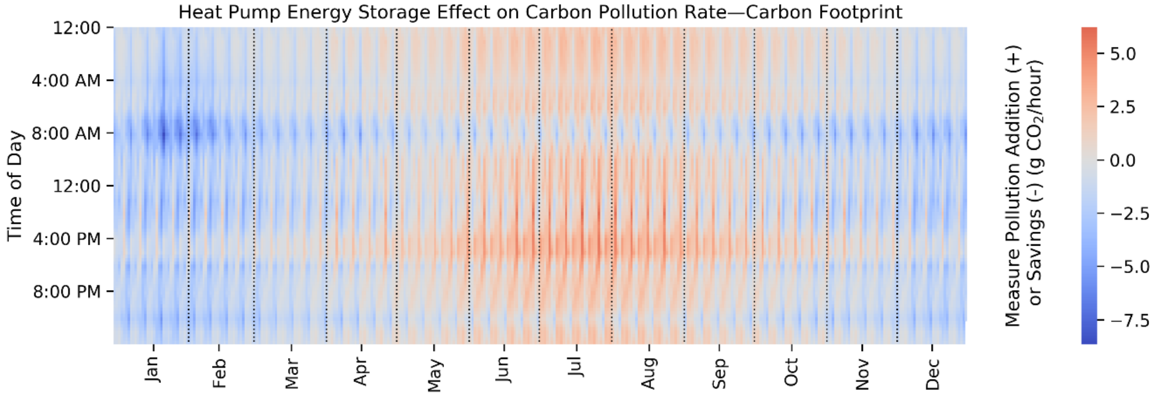
Energy Star Washer Effect on Carbon Pollution Rate—Carbon Footprint

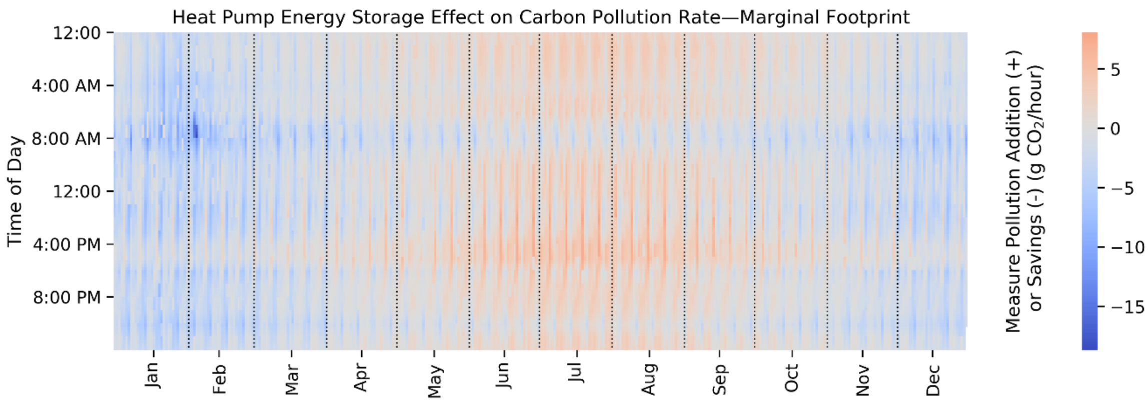


Energy Star Washer Effect on Carbon Pollution Rate—Marginal Footprint

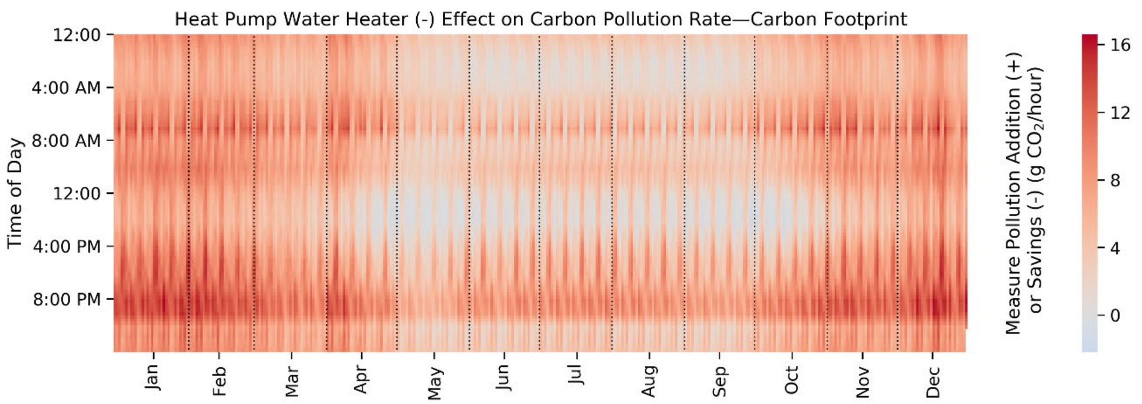


Heat Pump Energy Storage Effect on Carbon Pollution Rate—Carbon Footprint

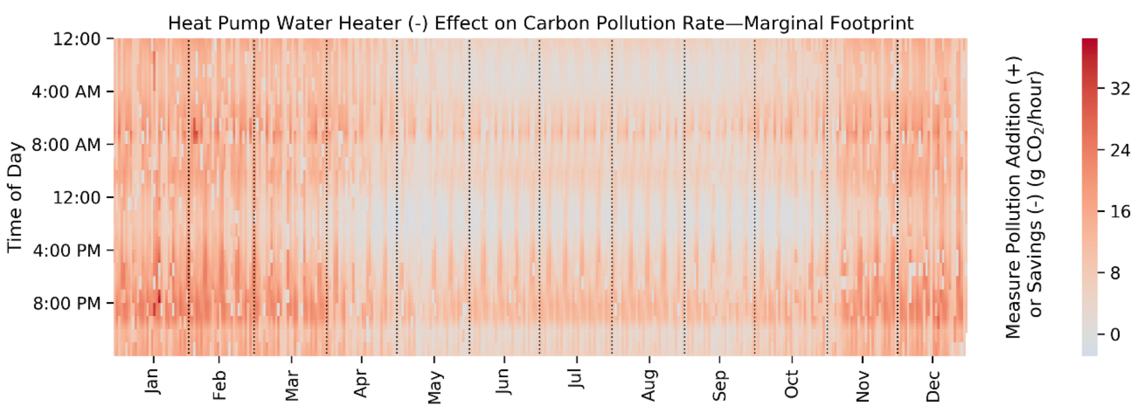




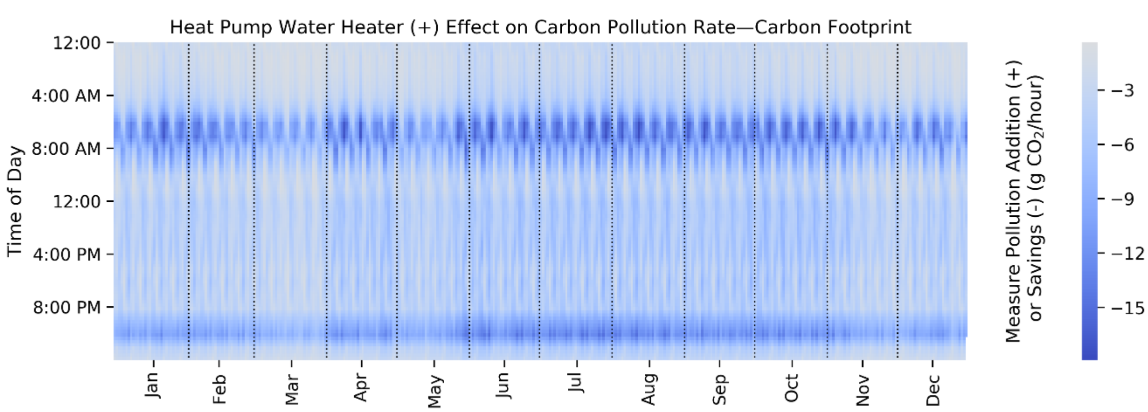
Heat Pump Energy Storage Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
5
0
−5
−10
−15



Heat Pump Water Heater (-) Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
16
12
8
4
0

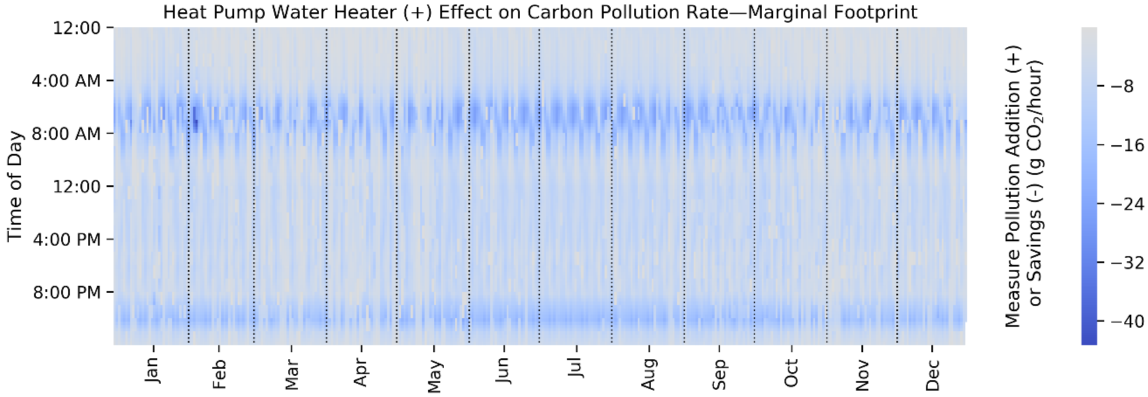


Heat Pump Water Heater (-) Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
32
24
16
8
0

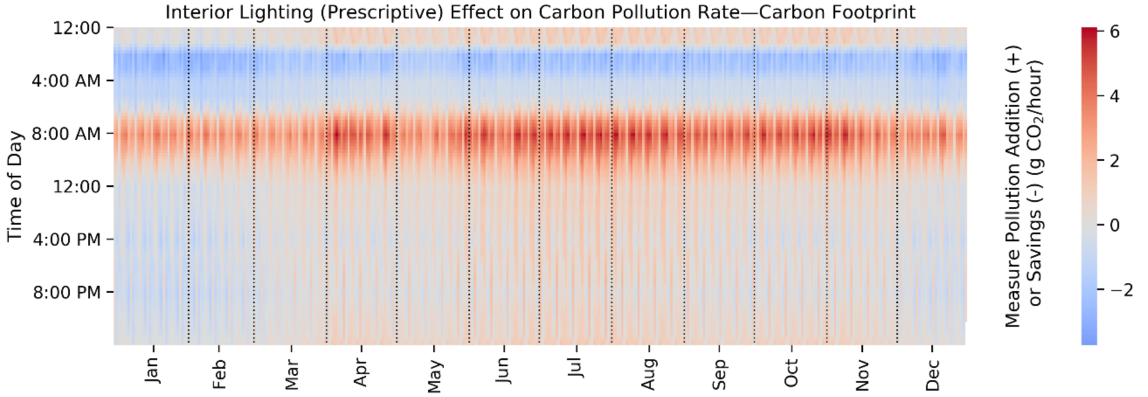


Heat Pump Water Heater (+) Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
−3
−6
−9
−12
−15

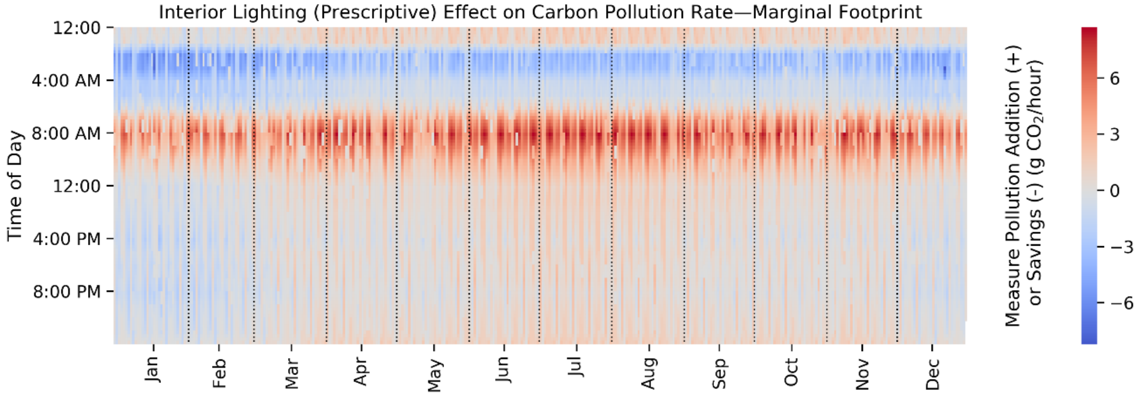
Heat Pump Water Heater (+) Effect on Carbon Pollution Rate—Marginal Footprint



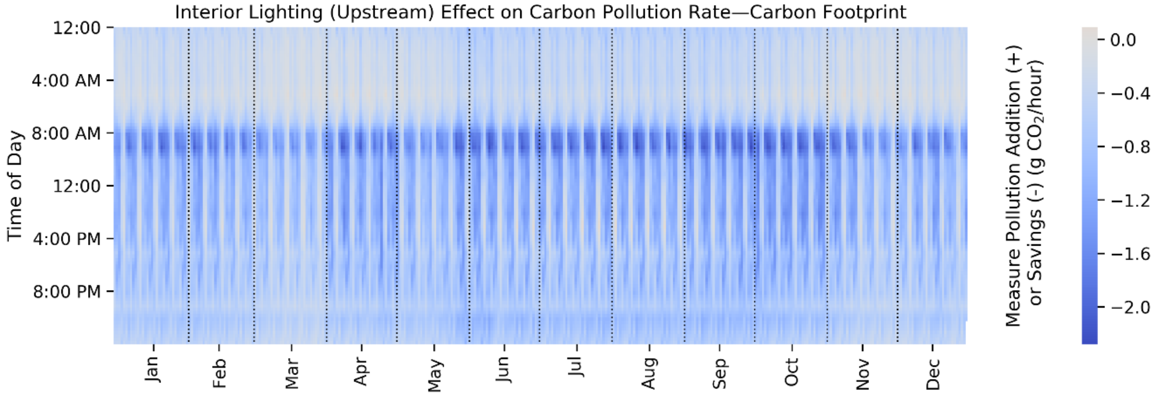
Interior Lighting (Prescriptive) Effect on Carbon Pollution Rate—Carbon Footprint

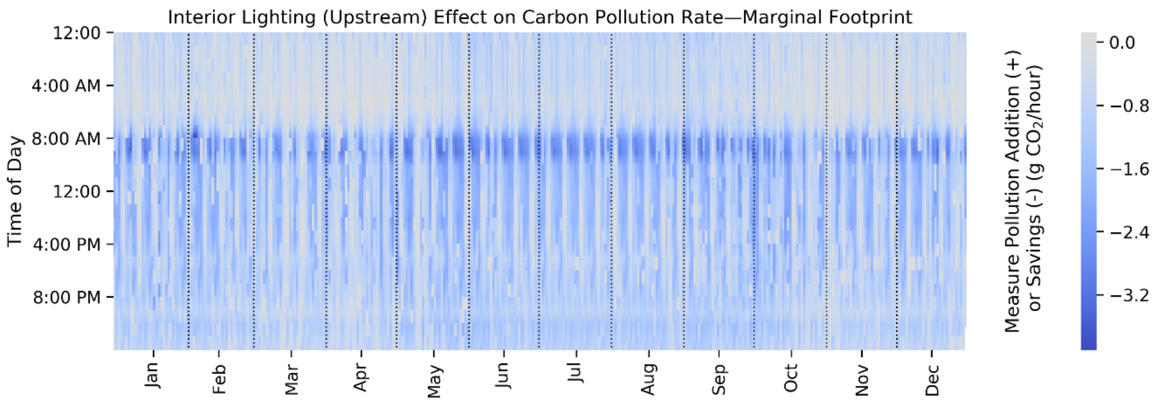


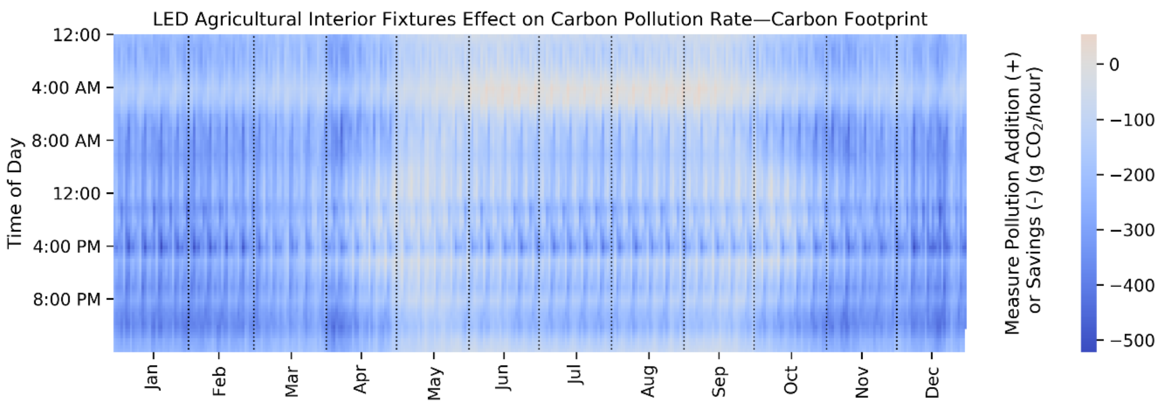
Interior Lighting (Prescriptive) Effect on Carbon Pollution Rate—Marginal Footprint

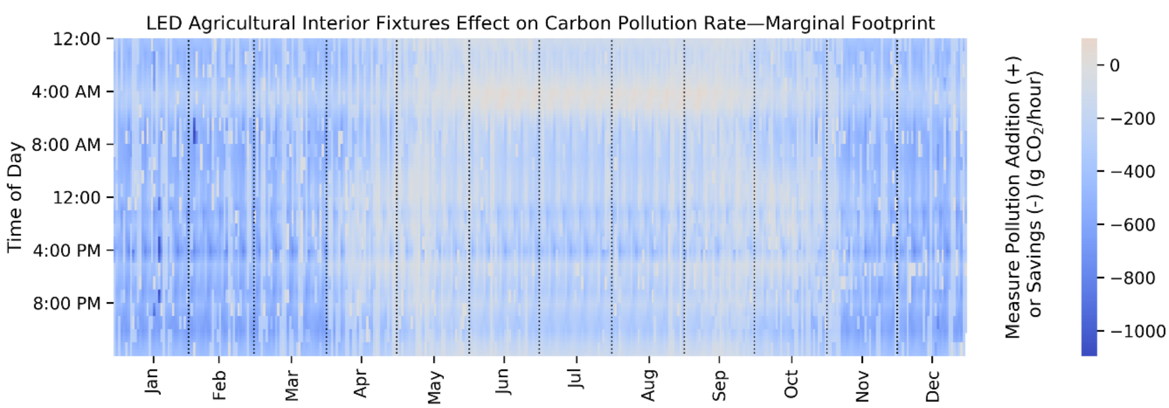


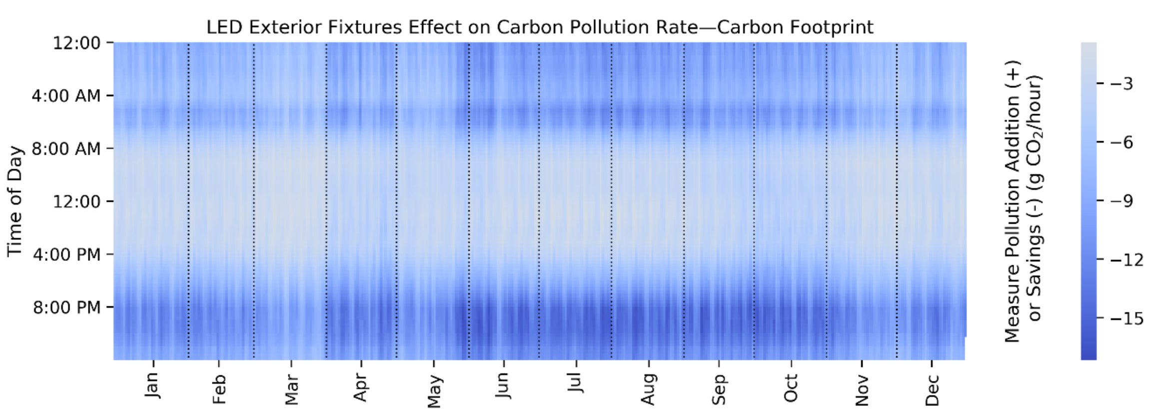
Interior Lighting (Upstream) Effect on Carbon Pollution Rate—Carbon Footprint

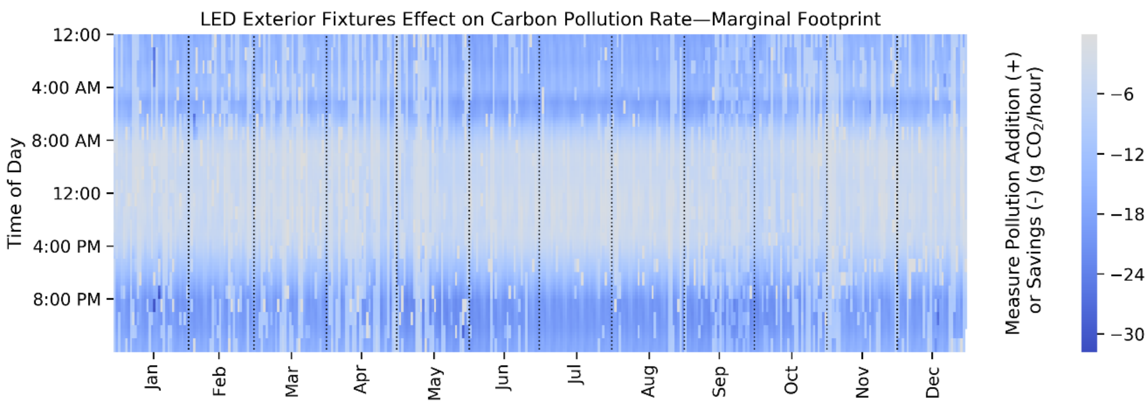


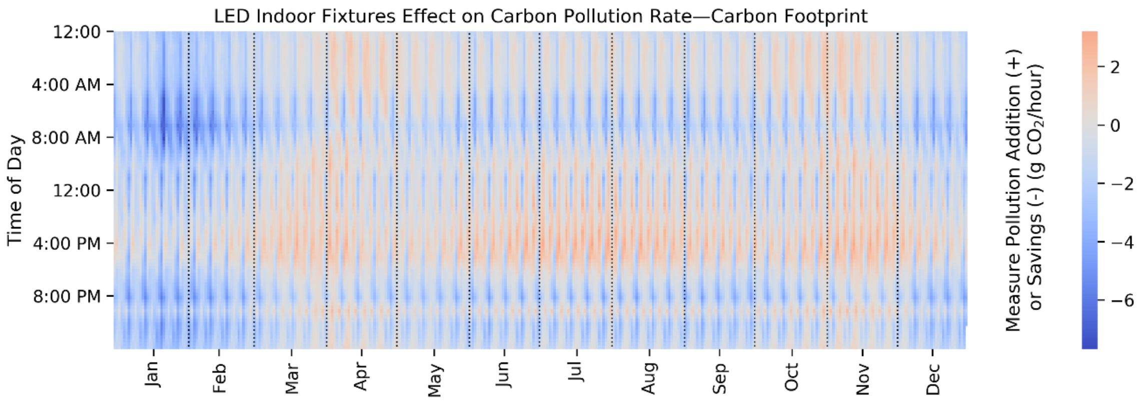

Interior Lighting (Upstream) Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
0.0
−0.8
−1.6
−2.4
−3.2

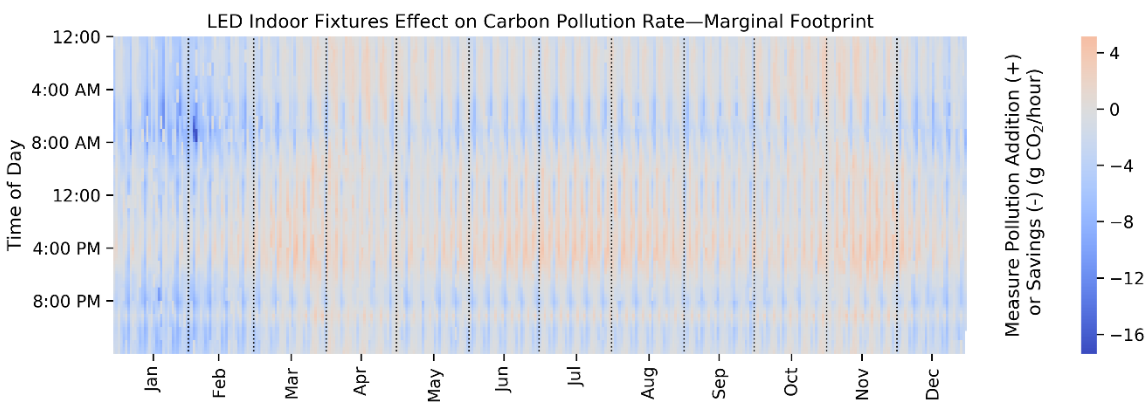

LED Agricultural Interior Fixtures Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
0
−100
−200
−300
−400
−500

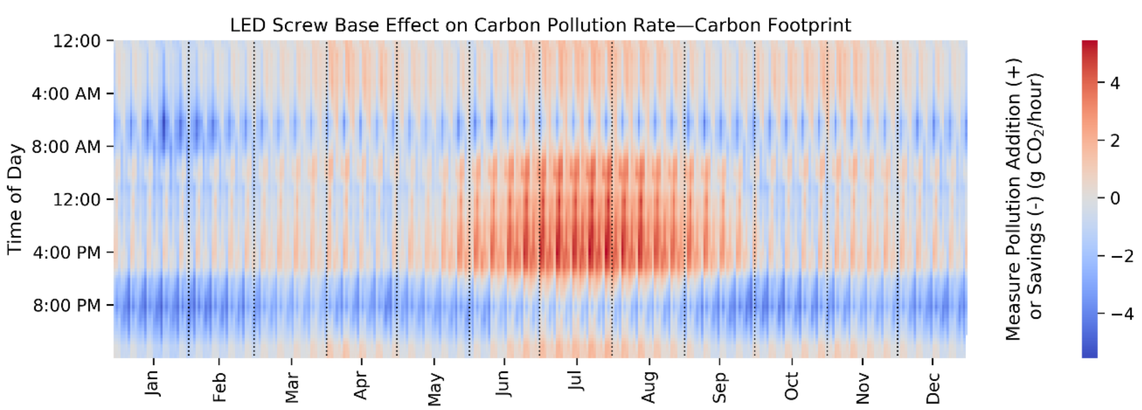

LED Agricultural Interior Fixtures Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
0
−200
−400
−600
−800
−1000

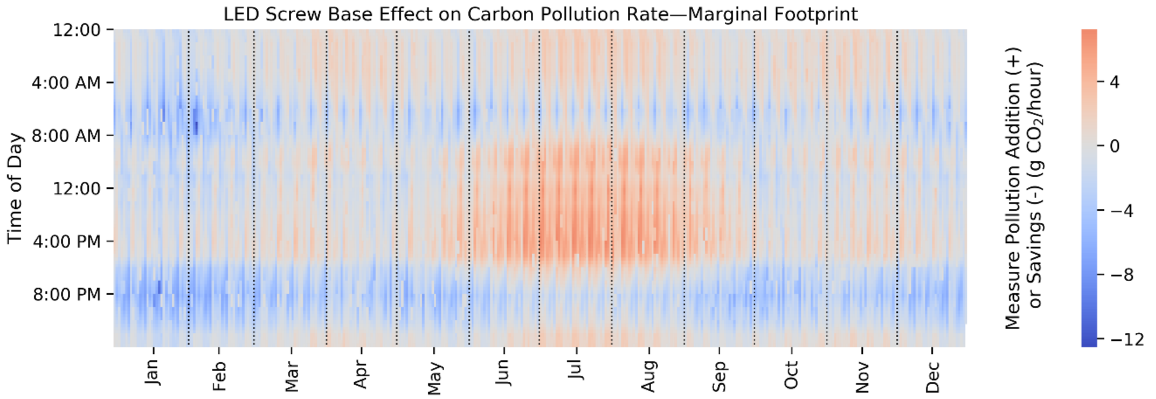

LED Exterior Fixtures Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
−3
−6
−9
−12
−15

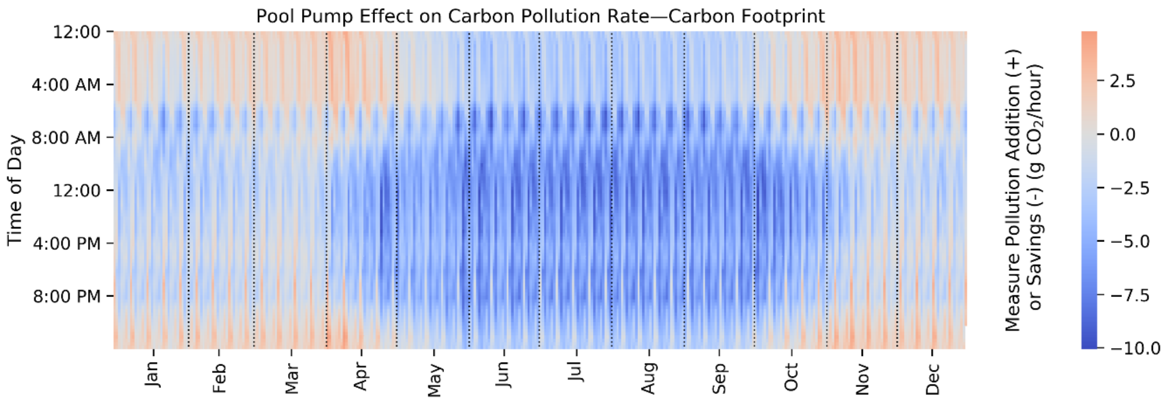

LED Exterior Fixtures Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
−6
−12
−18
−24
−30

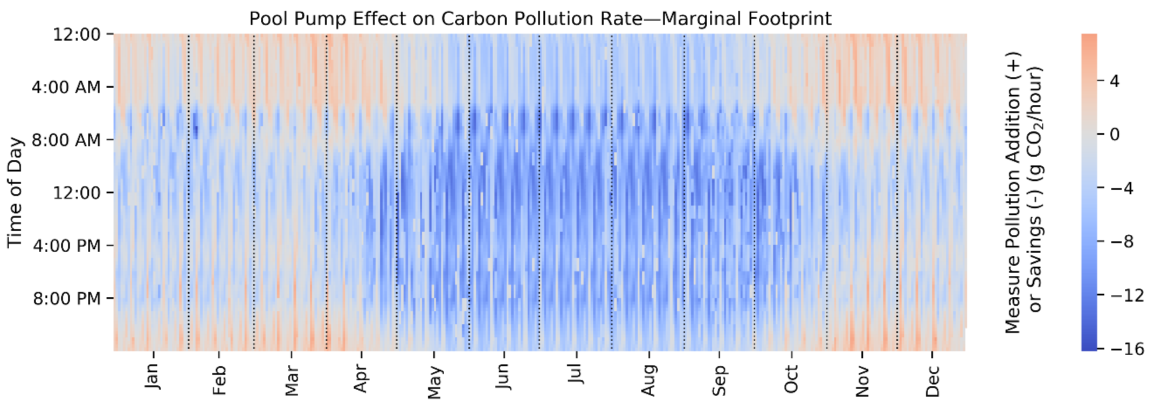

LED Indoor Fixtures Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
2
0
−2
−4
−6

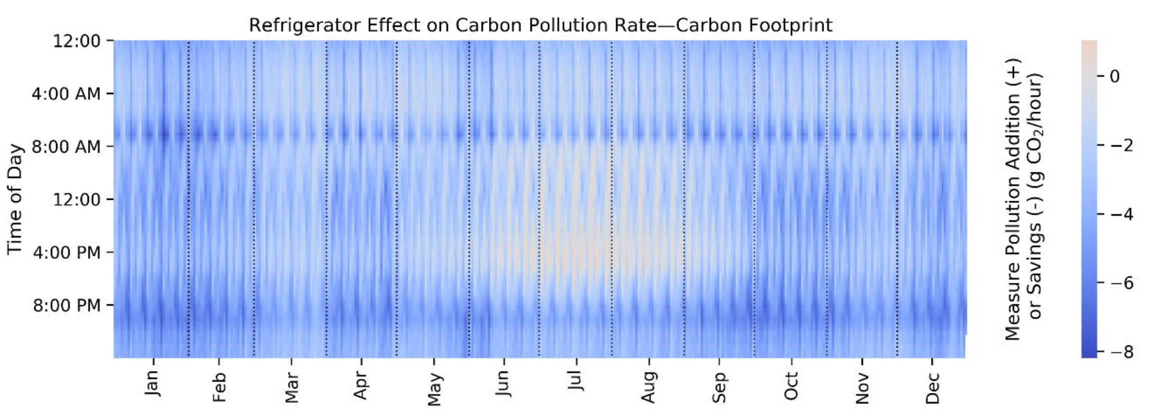

LED Indoor Fixtures Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
4
0
−4
−8
−12
−16

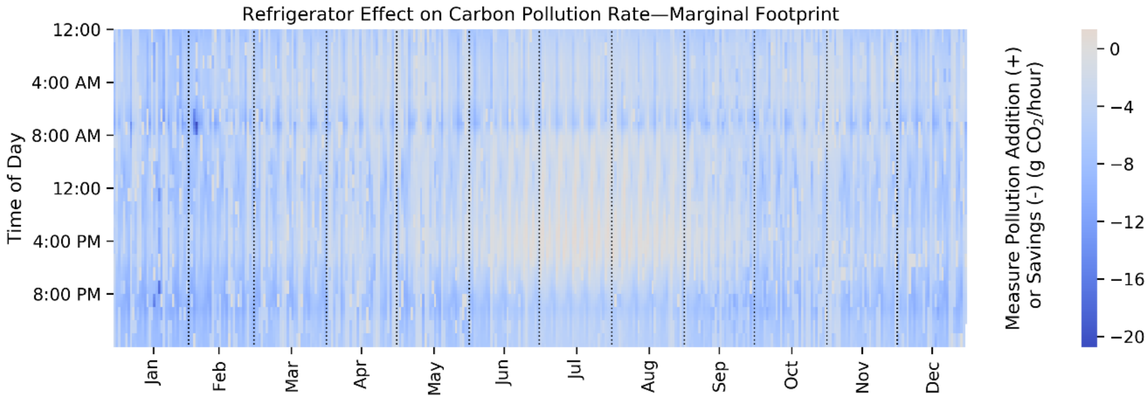

LED Screw Base Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
4
2
0
−2
−4


LED Screw Base Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO2/hour)
4
0
−4
−8
−12

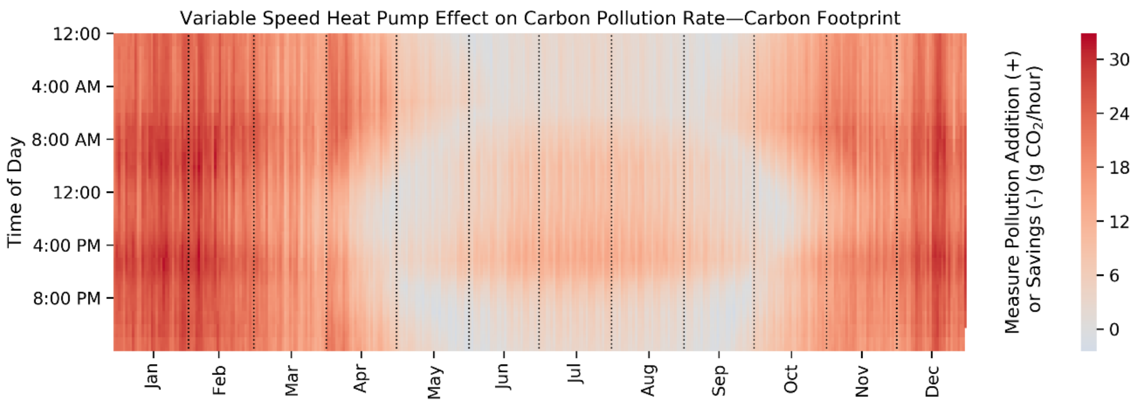

Pool Pump Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO2/hour)
2.5
0.0
−2.5
−5.0
−7.5
−10.0


Pool Pump Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO2/hour)
4
0
−4
−8
−12
−16

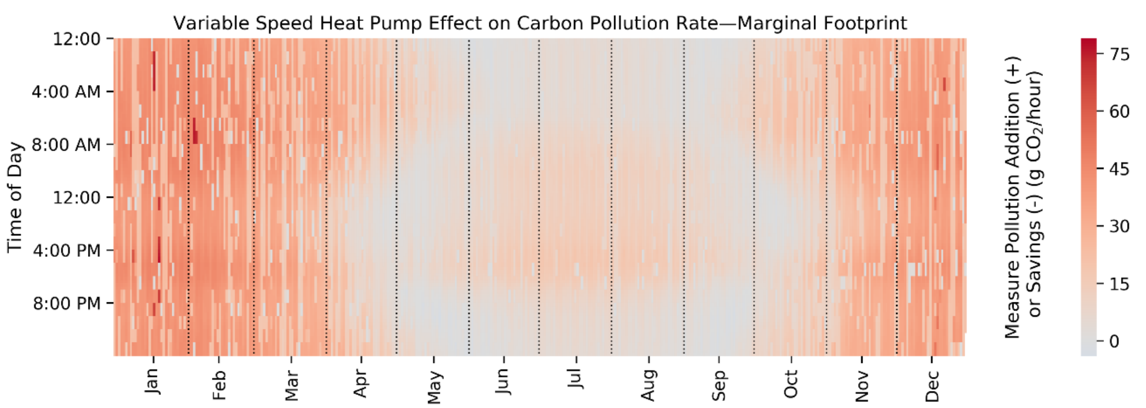

Refrigerator Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO2/hour)
0
−2
−4
−6
−8



Refrigerator Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
0
−4
−8
−12
−16
−20



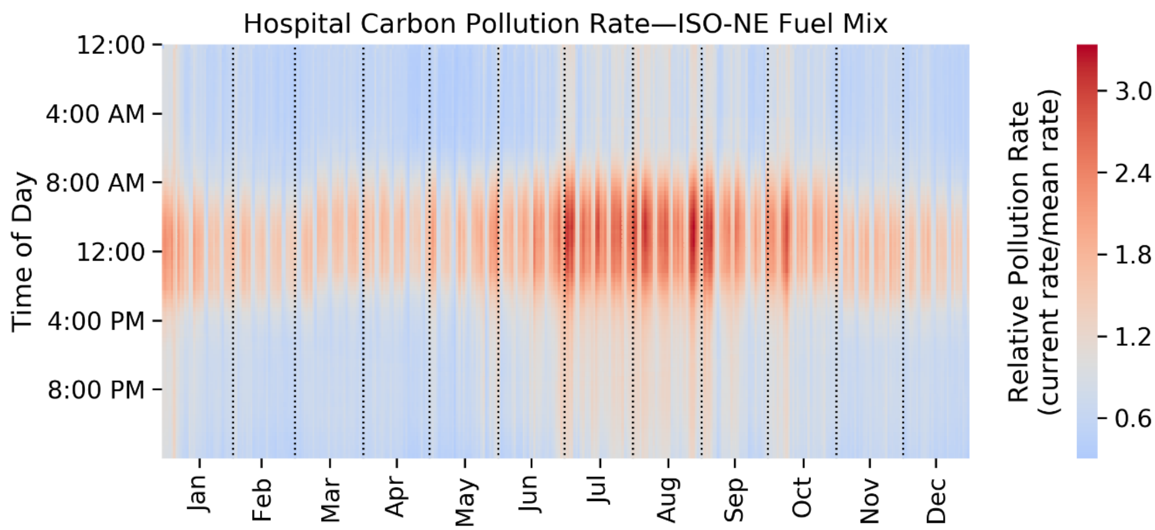
Variable Speed Heat Pump Effect on Carbon Pollution Rate—Carbon Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
30
24
18
12
6
0

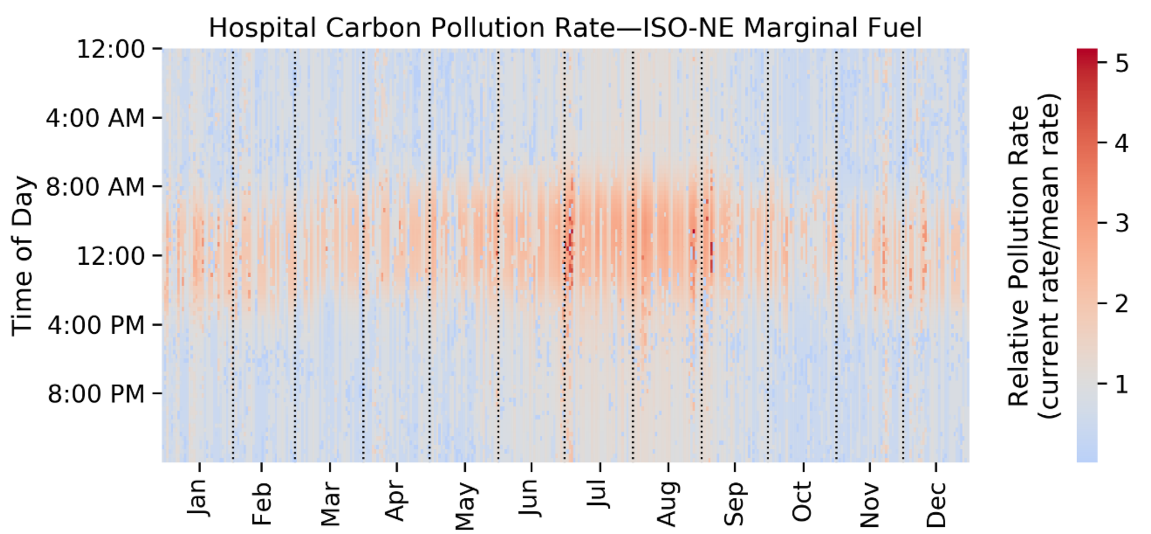


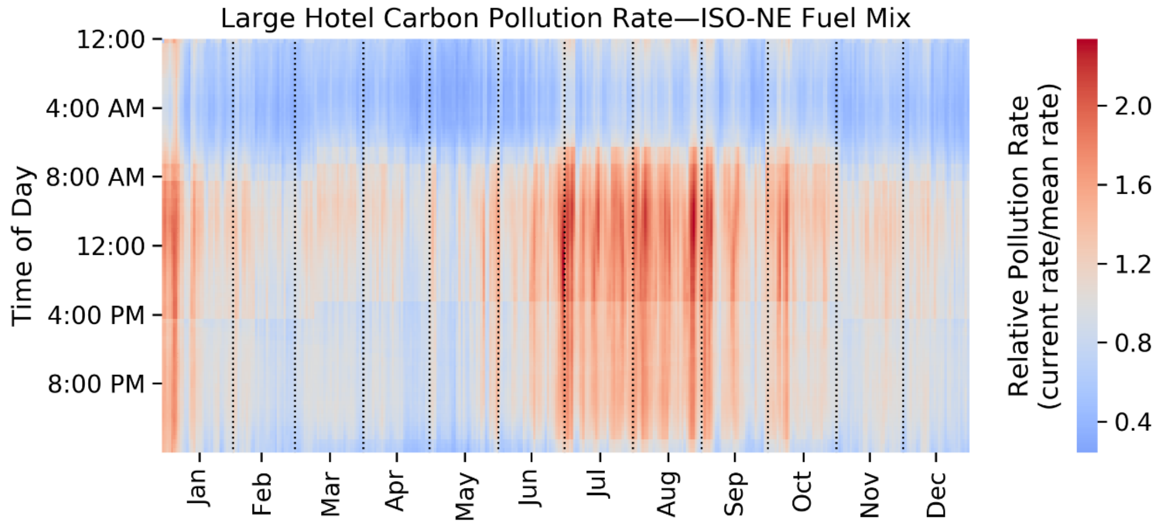
Variable Speed Heat Pump Effect on Carbon Pollution Rate—Marginal Footprint
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Measure Pollution Addition (+) or Savings (-) (g CO_2/hour)
75
60
45
30
15
0

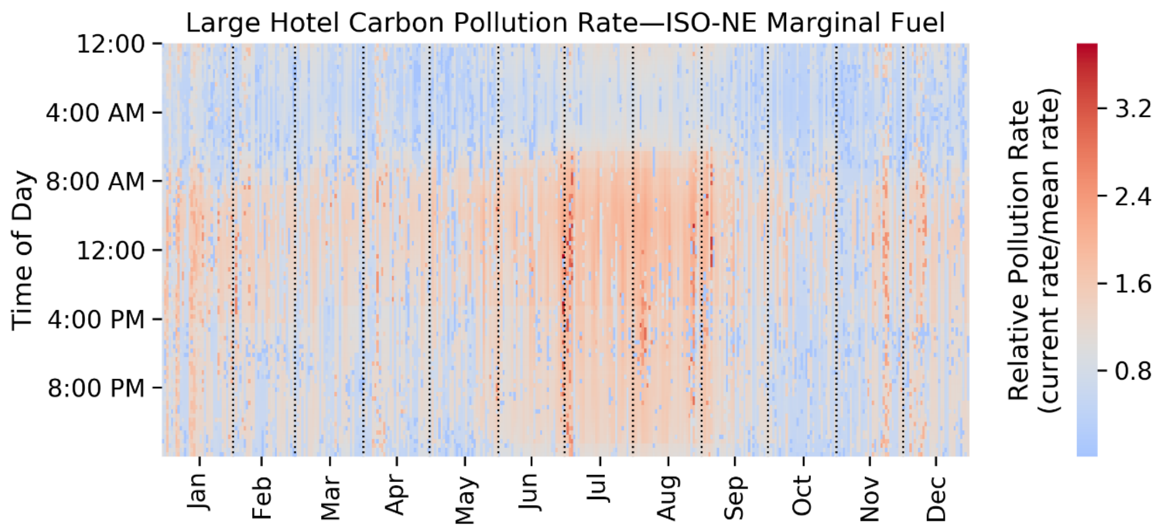
Appendix C—Emissions Shapes and Heatmaps by NREL Building Load Shape

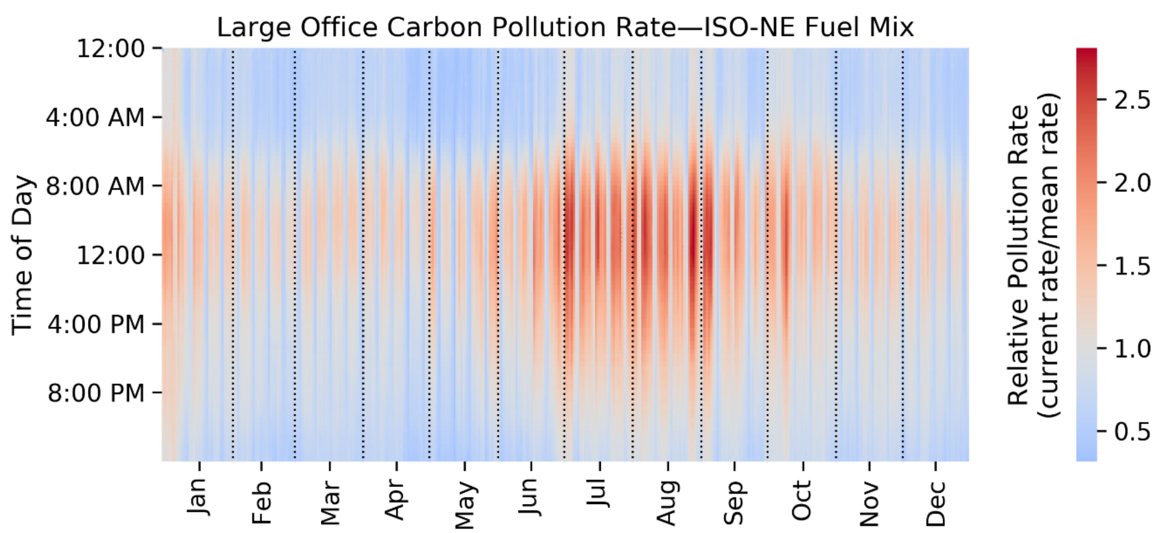
A selection of residential and commercial building emissions shapes from NREL's database for the ISO-NE region appears below.

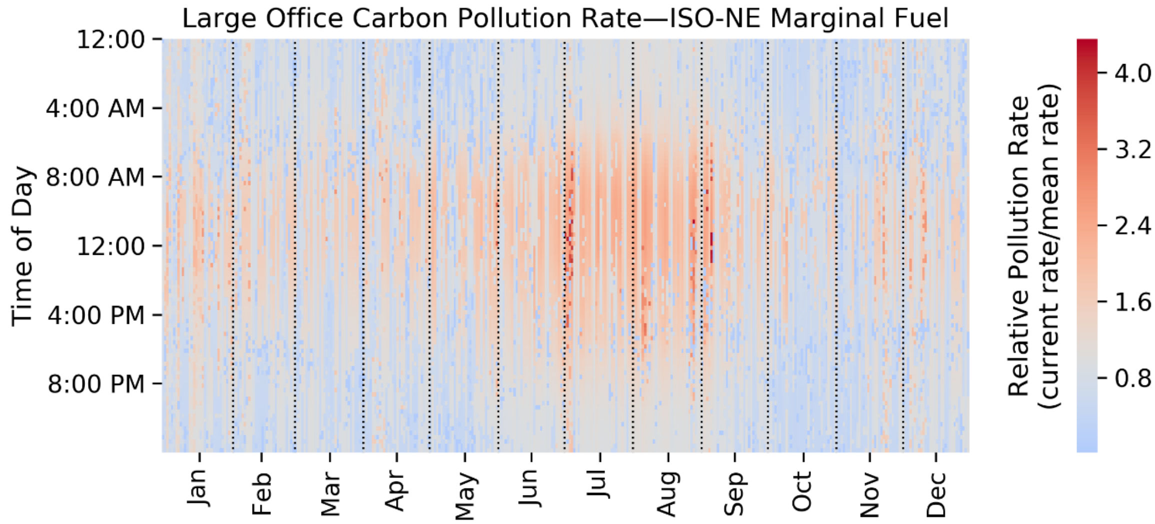


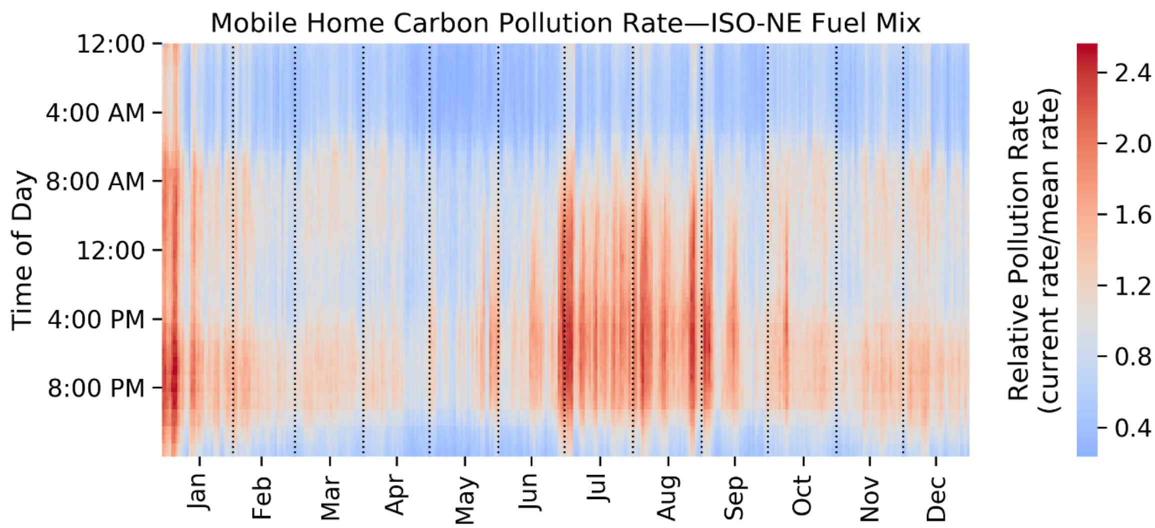


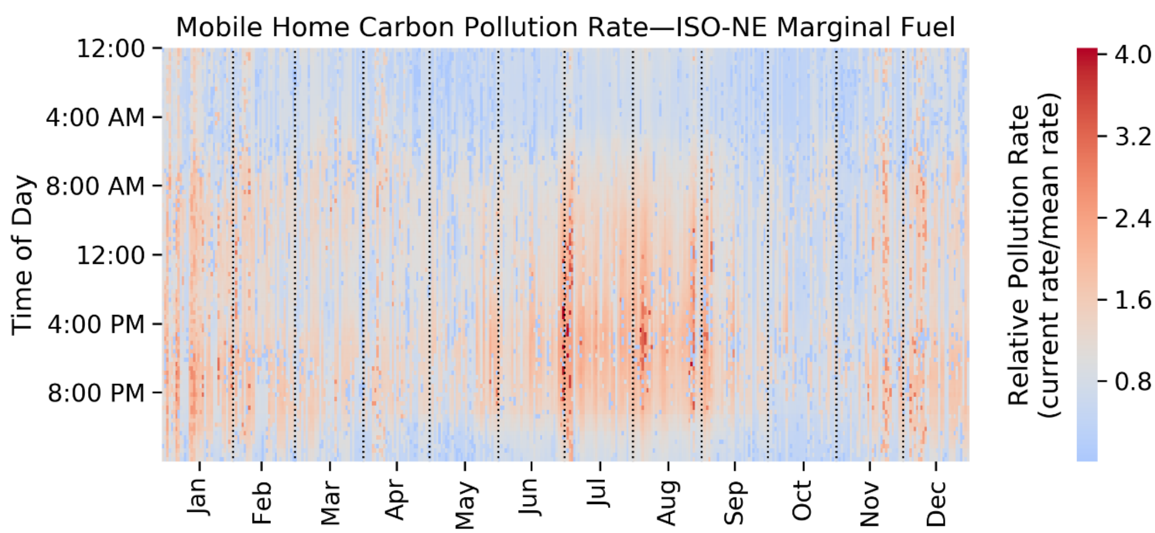

Large Hotel Carbon Pollution Rate—ISO-NE Fuel Mix
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
2.0
1.6
1.2
0.8
0.4

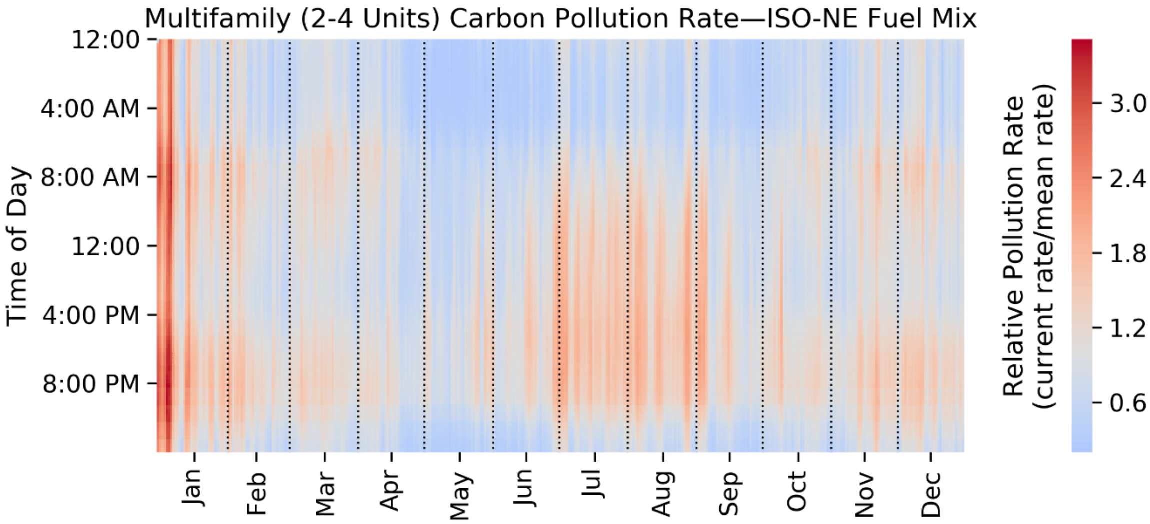

Large Hotel Carbon Pollution Rate—ISO-NE Marginal Fuel
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
3.2
2.4
1.6
0.8


Large Office Carbon Pollution Rate—ISO-NE Fuel Mix
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
2.5
2.0
1.5
1.0
0.5

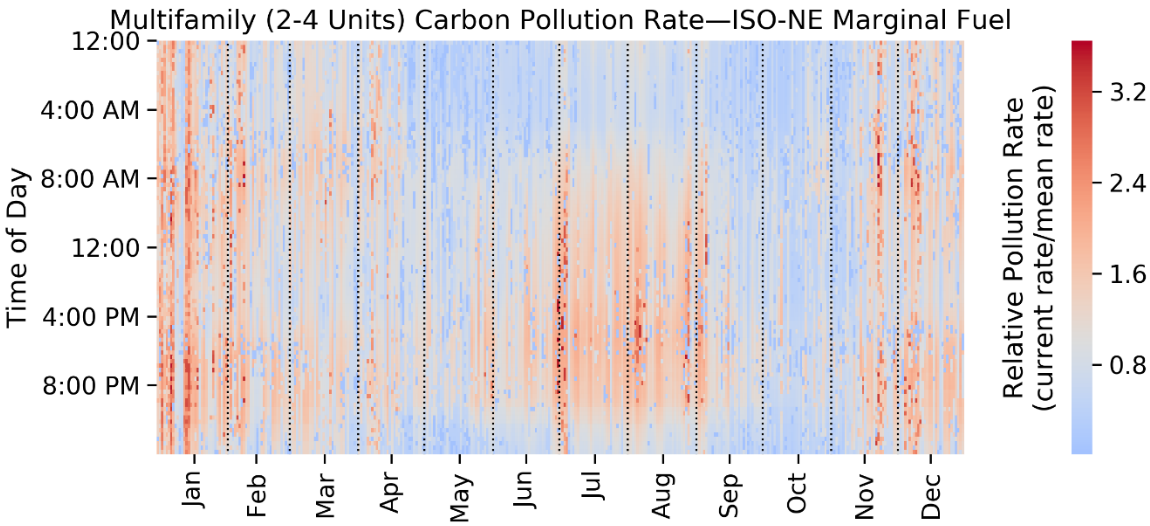

Large Office Carbon Pollution Rate—ISO-NE Marginal Fuel
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
4.0
3.2
2.4
1.6
0.8


Mobile Home Carbon Pollution Rate—ISO-NE Fuel Mix
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
2.4
2.0
1.6
1.2
0.8
0.4

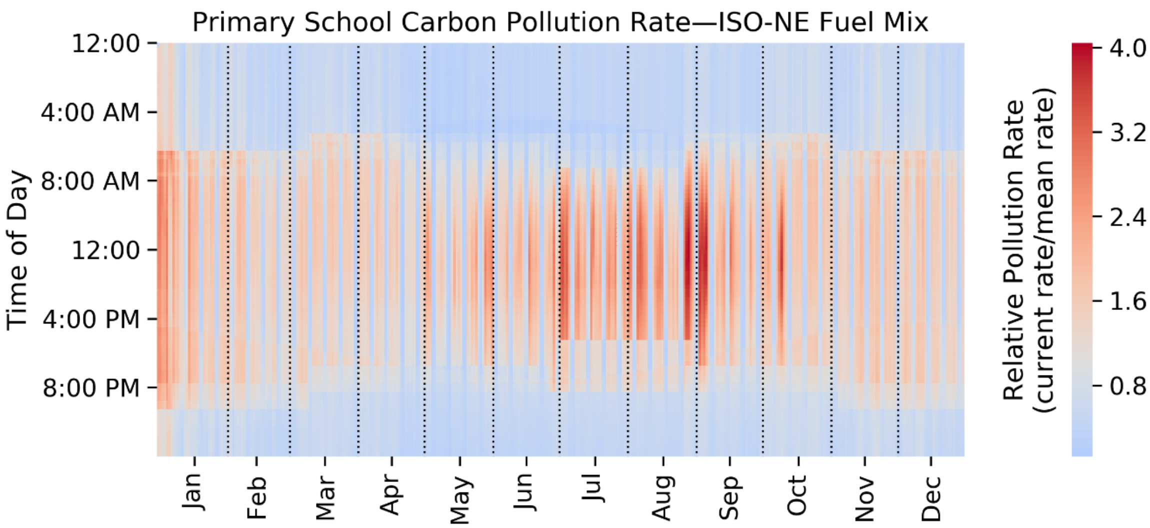

Mobile Home Carbon Pollution Rate—ISO-NE Marginal Fuel
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
4.0
3.2
2.4
1.6
0.8



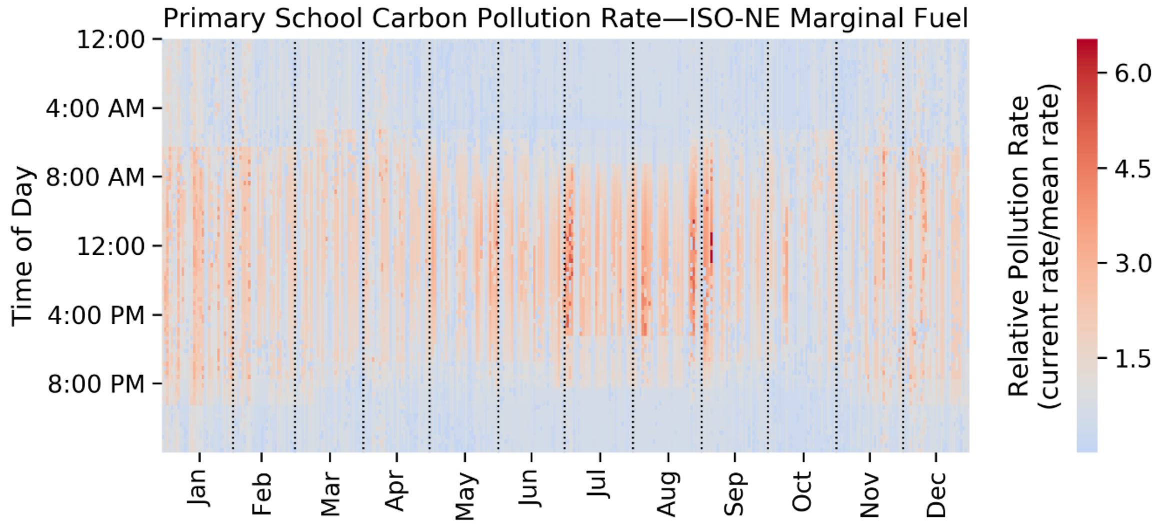
Multifamily (2-4 Units) Carbon Pollution Rate—ISO-NE Fuel Mix
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
3.0
2.4
1.8
1.2
0.6

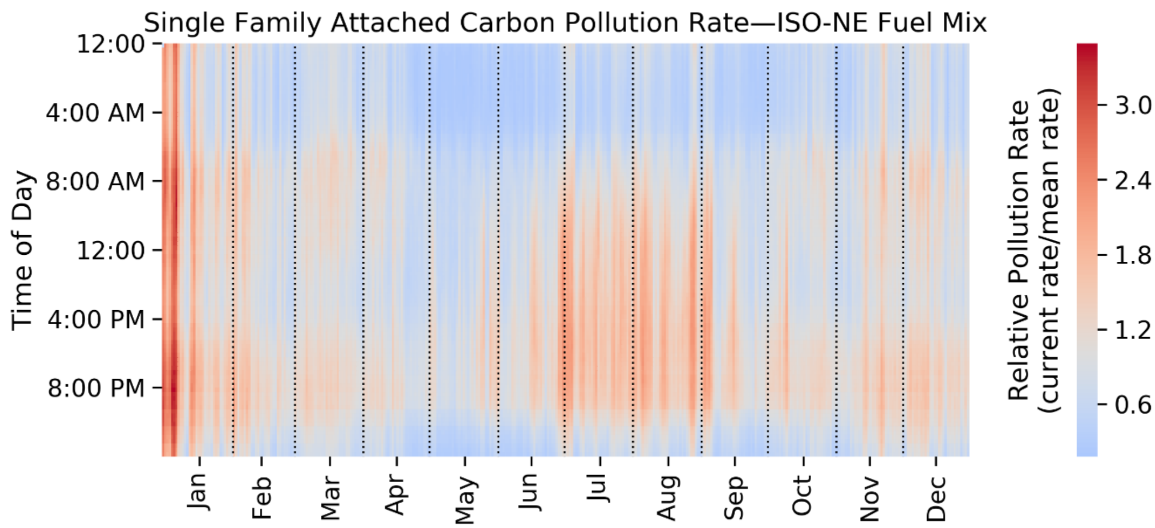


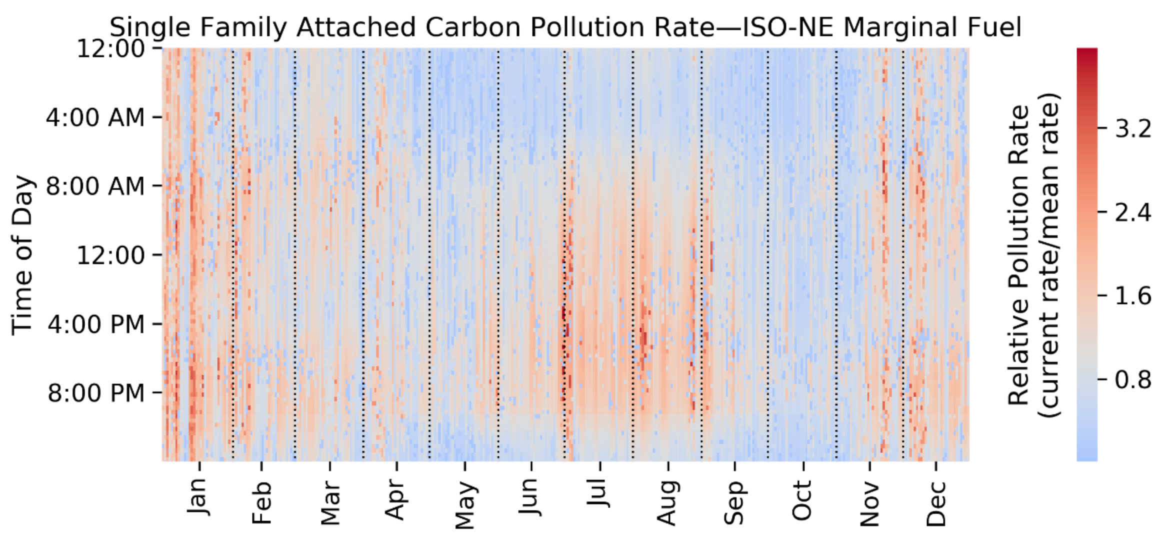
Multifamily (2-4 Units) Carbon Pollution Rate—ISO-NE Marginal Fuel
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
3.2
2.4
1.6
0.8

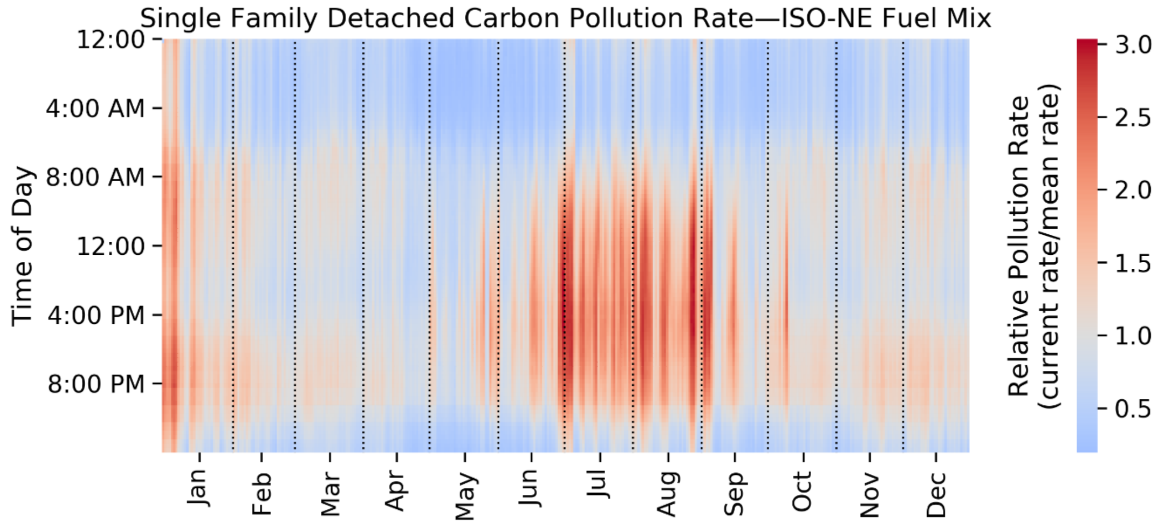


Primary School Carbon Pollution Rate—ISO-NE Fuel Mix
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
4.0
3.2
2.4
1.6
0.8

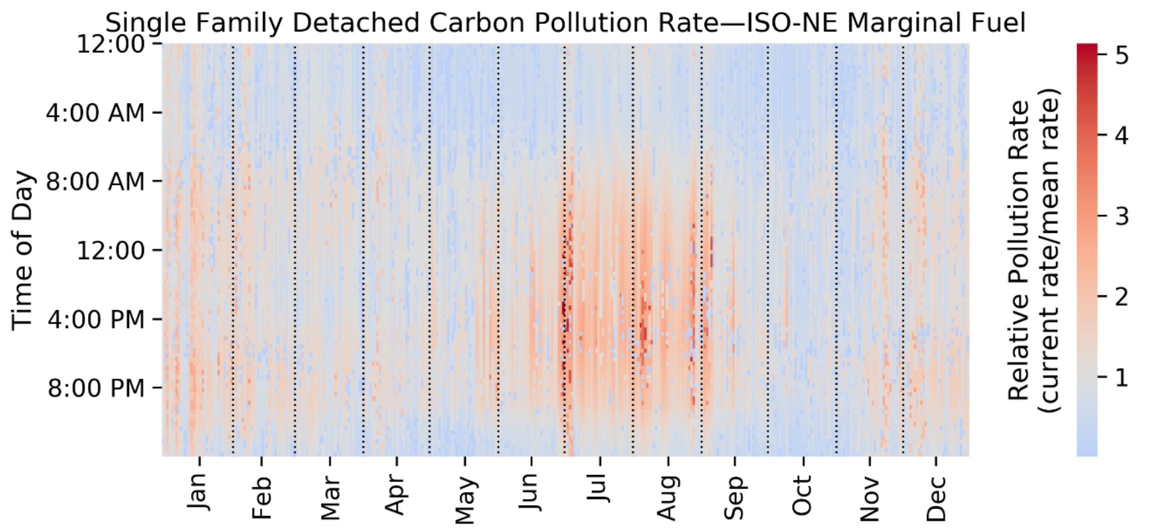

Primary School Carbon Pollution Rate—ISO-NE Marginal Fuel
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
6.0
4.5
3.0
1.5


Single Family Attached Carbon Pollution Rate—ISO-NE Fuel Mix
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
3.0
2.4
1.8
1.2
0.6

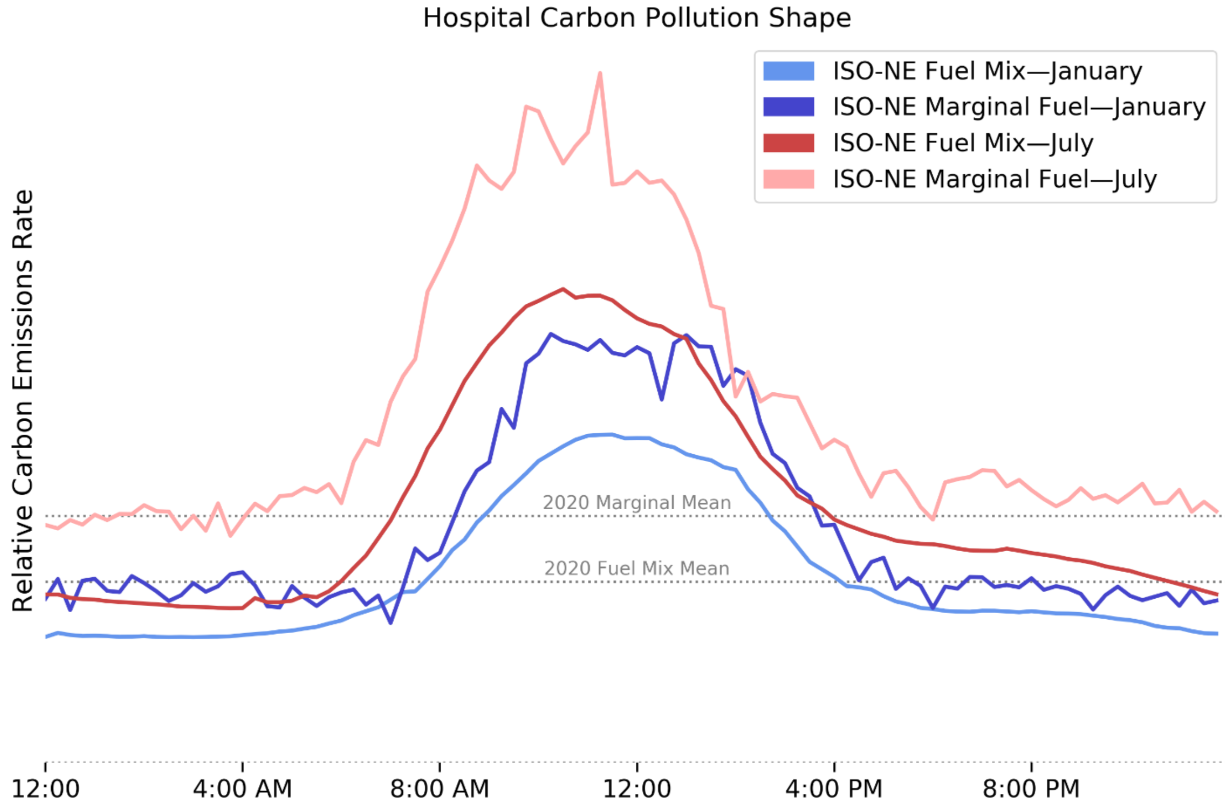

Single Family Attached Carbon Pollution Rate—ISO-NE Marginal Fuel
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
3.2
2.4
1.6
0.8

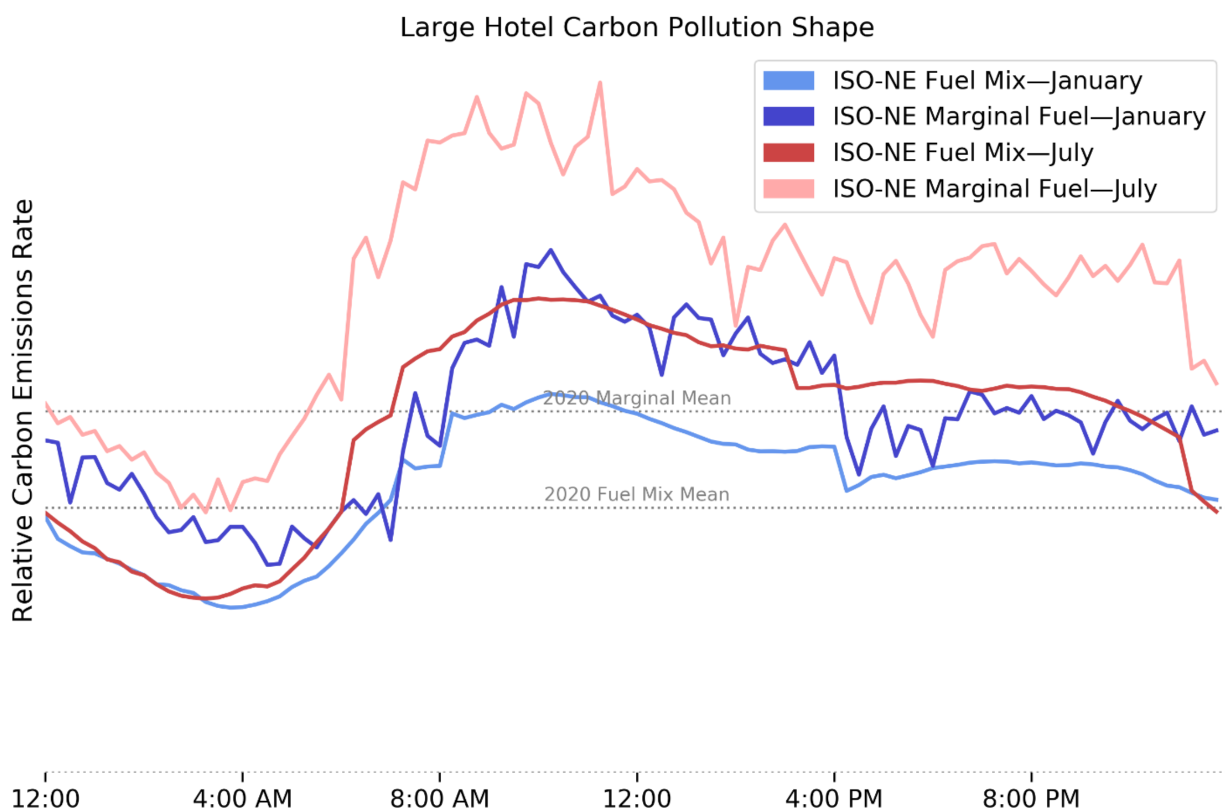


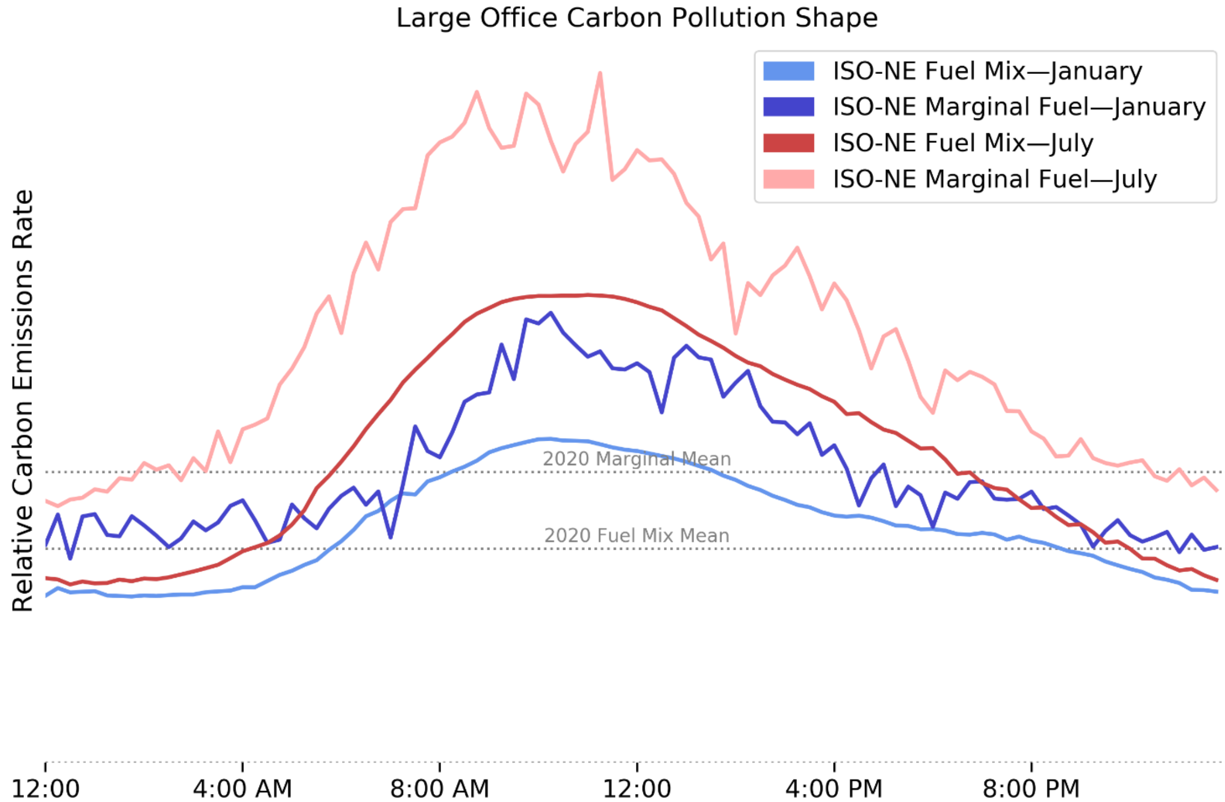
Single Family Detached Carbon Pollution Rate—ISO-NE Fuel Mix
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
3.0
2.5
2.0
1.5
1.0
0.5



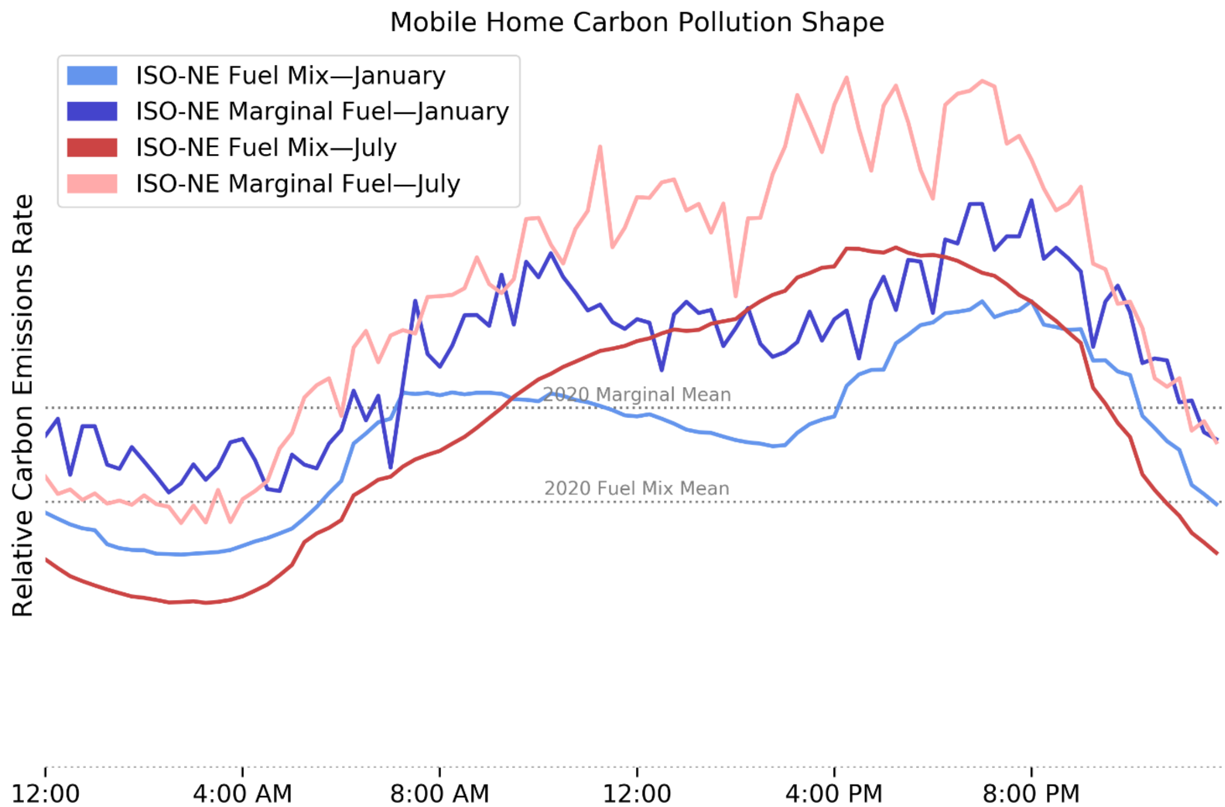
Single Family Detached Carbon Pollution Rate—ISO-NE Marginal Fuel
Time of Day
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Relative Pollution Rate
(current rate/mean rate)
5
4
3
2
1


Hospital Carbon Pollution Shape
ISO-NE Fuel Mix—January
ISO-NE Marginal Fuel—January
ISO-NE Fuel Mix—July
ISO-NE Marginal Fuel—July
Relative Carbon Emissions Rate
2020 Marginal Mean
2020 Fuel Mix Mean
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM


Large Hotel Carbon Pollution Shape
ISO-NE Fuel Mix—January
ISO-NE Marginal Fuel—January
ISO-NE Fuel Mix—July
ISO-NE Marginal Fuel—July
Relative Carbon Emissions Rate
2020 Marginal Mean
2020 Fuel Mix Mean
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

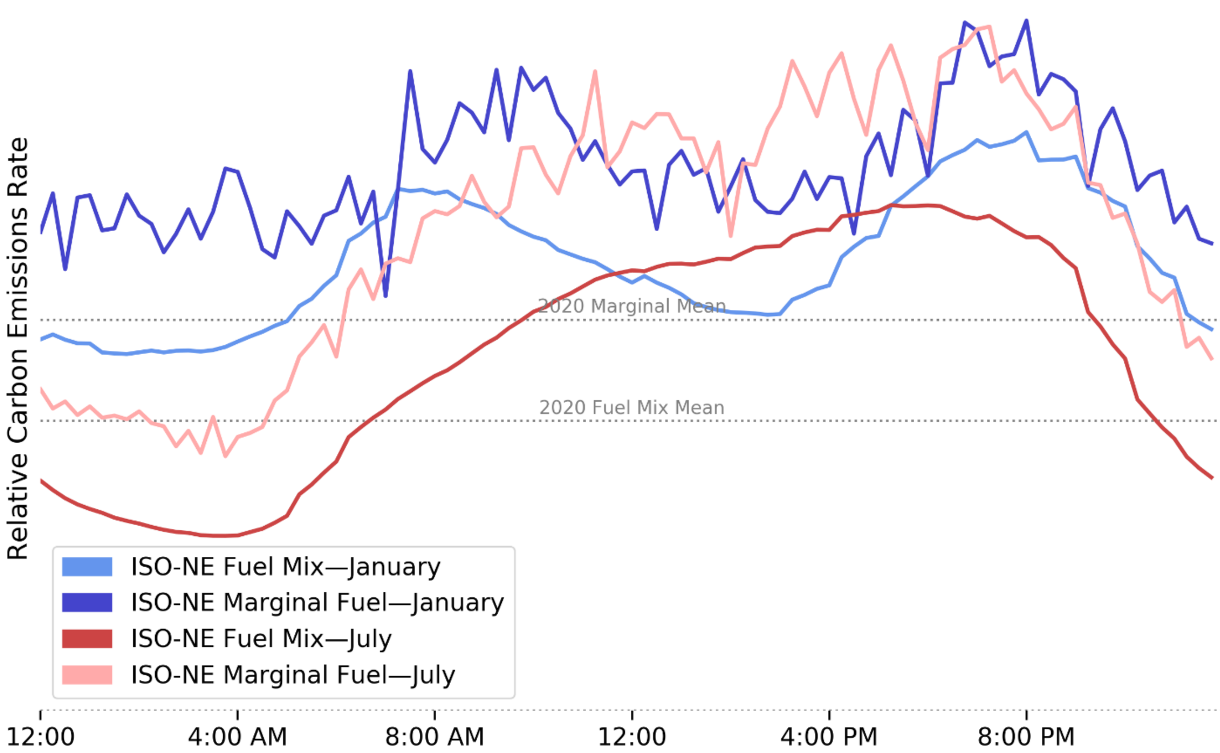


Large Office Carbon Pollution Shape
ISO-NE Fuel Mix—January
ISO-NE Marginal Fuel—January
ISO-NE Fuel Mix—July
ISO-NE Marginal Fuel—July
Relative Carbon Emissions Rate
2020 Marginal Mean
2020 Fuel Mix Mean
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

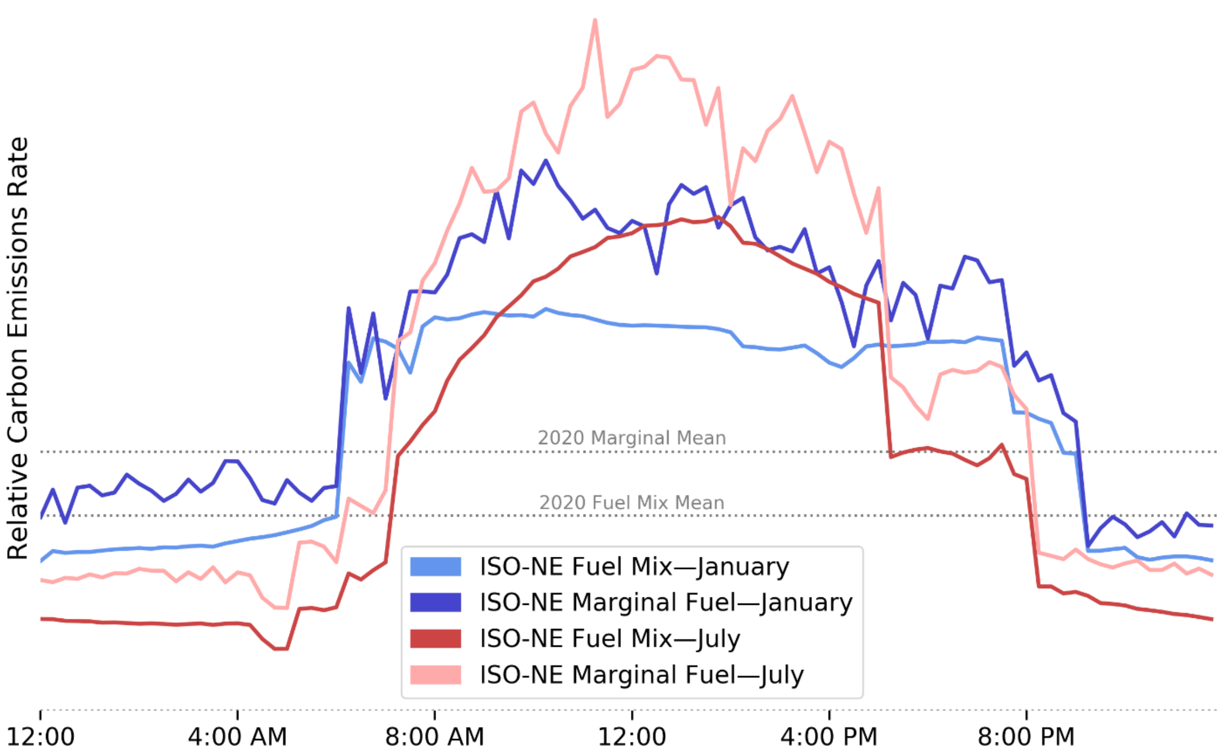


Mobile Home Carbon Pollution Shape
ISO-NE Fuel Mix—January
ISO-NE Marginal Fuel—January
ISO-NE Fuel Mix—July
ISO-NE Marginal Fuel—July
Relative Carbon Emissions Rate
2020 Marginal Mean
2020 Fuel Mix Mean
12:00
4:00 AM
8:00 AM
12:00
4:00 PM
8:00 PM

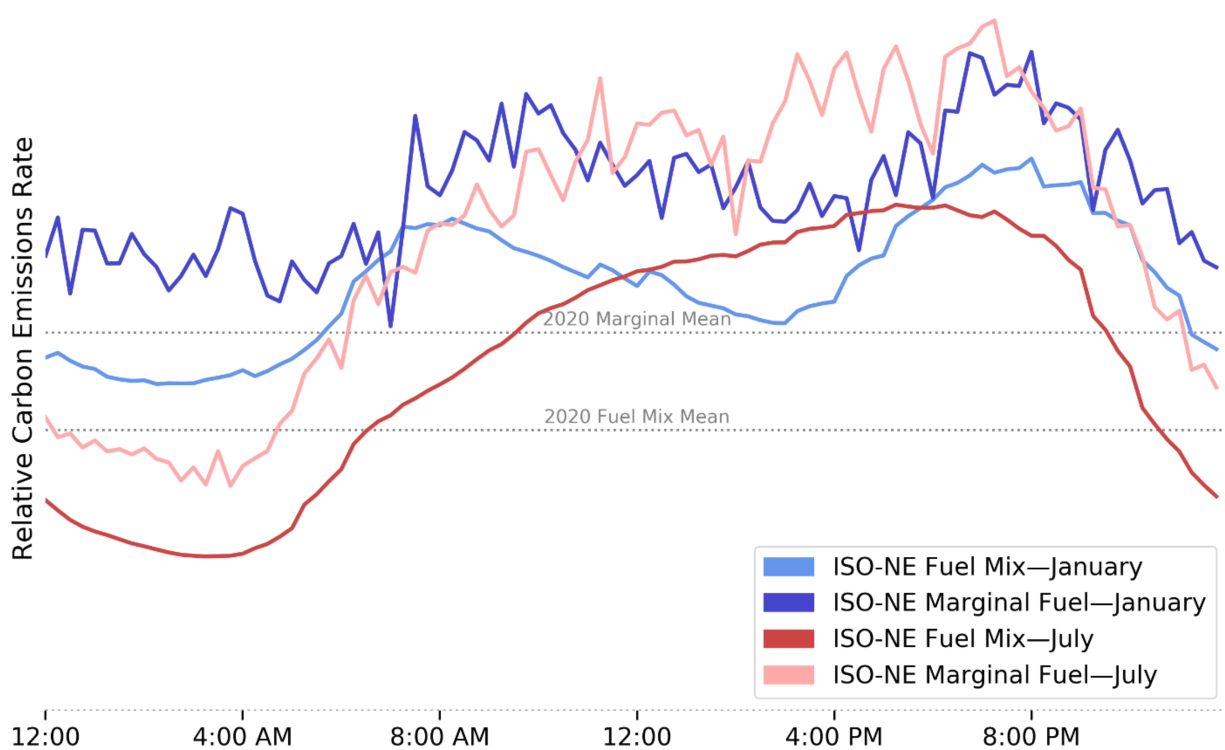
Multifamily (2-4 Units) Carbon Pollution Shape



Primary School Carbon Pollution Shape



Single Family Attached Carbon Pollution Shape



Single Family Detached Carbon Pollution Shape