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Field Evaluation of Direct Heating Equipment in California

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Abstract

This report presents a multi-year field evaluation assessment of the real-world performance of direct heating equipment (DHE) across 11 California households. The goal was to obtain empirical data on DHE operation, energy use, thermal comfort provided, and impacts on indoor air quality. We first monitored the performance of existing low-efficiency DHE units over one heating season to establish a baseline. Subsequently, 10 of these units were replaced with high-efficiency direct-vent and upright wall furnaces, which were then monitored over the following two heating seasons. It should be noted that the sample of 11 households is small, and the findings should be interpreted with caution, as they do not represent the broader DHE fleet in California and the United States.

Results from the 10 sites indicate that high-efficiency DHE significantly improved thermal comfort, producing faster space warming and better distributing warm air. Natural gas consumption per heating degree day decreased at six of the monitored sites. However, gas usage increased at four sites, likely due to a "rebound effect" in which users operated their new heaters more frequently or for longer periods to take advantage of improved thermal comfort and enhanced thermostat controls. While the rebound effect may have reduced energy savings, the increased use of the heater has also led to higher consumer welfare, as reflected in better thermal comfort from the additional energy consumption.

Field data also indicate that, in some cases, indoor concentrations of carbon dioxide and carbon monoxide in the direct-heated space increase during heater operation, and that these increases are lower with high-efficiency units than with low-efficiency units. While household behavior and other household sources of carbon dioxide and carbon monoxide likely contributed to the increases, we do not rule out the possibility that the heaters might also have played a role. The data also show some changes in indoor concentrations of particulate matter and total volatile organic compounds, but they do not provide sufficient evidence of an association between heater operation and these changes. Despite increases in pollutant concentrations during heater operation, we did not observe any critical exposure levels under regular operating conditions. However, during two events at different sites, the monitoring system detected that newly installed units were leaking elevated levels of carbon monoxide into living spaces, requiring immediate shutdown and replacement. In both cases, the units were diagnosed as malfunctioning due to manufacturing defects.

Finally, while user feedback validated the improvements in heating speed and distribution, overall satisfaction was considerably hindered by equipment noise. Multiple households found the new circulation and combustion fans too loud for living spaces. The report concludes with recommendations for future improvements to DHE.

This report is part of the deliverables of the technical task “Task 3: Laboratory and Field Evaluation” of the California Energy Commission (CEC)-funded project “Cost-Effective Technologies and Strategies to Improve Energy Efficiency and Reduce Emissions of Direct Heating Equipment in California with Health Benefits” (Grant Agreement No. PIR-18-006,

signed in October 2019). The goal of the task is to “obtain empirical data on current DHE energy use, size appropriateness, emissions, and indoor air quality and thermal comfort of households where they are used” (Grant Agreement PIR-18-006). This report focuses solely on field evaluations. The laboratory evaluations are reported in Blum et al. (2024b).

1. Introduction

Direct heating equipment (DHE) is a type of space-heating appliance. DHE is ductless and delivers warm air directly to the surrounding area where it is installed. The three types of DHE are wall furnaces, room heaters, and floor furnaces. Figure 1 shows examples of DHE models.[1] Wall furnaces can be upright or console-style and are typically attached to the wall. Room heaters also have a console-style shape, but are detached from the wall. Floor furnaces are installed directly beneath the floor, in a basement or a crawl space.

Figure 1. Examples of DHE

Source: Blum et al. (2024a). (Courtesy of Williams Comfort Products, www.williamscomfortprod.com.)

DHE has been estimated to be the primary or secondary source of space heating in approximately 13% of households in California (Blum and Ke, 2025), and has been addressed in prior field research on gas appliances. Singer et al. (2009) measured pollutant emissions in laboratory and residential settings in California, both before and during the burn cycles of a range of natural gas appliances, using varying natural gas qualities. The team found that although furnaces—including one wall furnace—and other appliances functioned normally

[1] These images represent only a small sample of DHE models available on the market. Reference to these specific DHE models or brands does not constitute or imply any endorsement, recommendation, or favor by the U.S. Department of Energy, the Regents of the University of California, the California Energy Commission, or Lawrence Berkeley National Laboratory.

across varying gas qualities, emissions of carbon monoxide (CO), nitrogen oxides (NO_x), nitrogen dioxide (NO_2), formaldehyde, and ultrafine particles varied by appliance and operational mode. In addition, while three of the four central furnaces evaluated showed increases of 1%, 3%, and 4% in NO_x emissions as fuel Wobbe Number increased,[2] there was no discernible change in NO_x emissions from the wall furnace.

Valmiki et al. (2013) investigated the potential energy savings from gravity wall furnace retrofits, in which old DHE units were replaced with new, higher-energy-efficient (71% AFUE[3]) gravity wall furnaces in a multi-family studio apartment complex. They found that DHE gas consumption decreased by 15%-55% in the retrofitted apartments, although the payback period would exceed the equipment's lifespan. They further found that standing pilot lights account for a significant amount of the wall furnace's annual gas use and recommend that utility rebate programs strongly encourage eliminating standing pilot lights (using intermittent spark or hot-surface ignition) to achieve significantly greater energy savings.

Mullen et al. (2012, 2016) conducted a 2-year study of air pollutants associated with the use of natural gas appliances in California. The team measured occupant activity and concentrations of CO, NO_2, NO_x, formaldehyde, and acetaldehyde in 352 homes. They observed higher levels of bedroom NO_2 in homes with floor- or wall-mounted furnaces that had pilot burners, indicating potential exposure-reduction benefits from improved ventilation and from replacing existing pilot-containing appliances with more efficient models to improve indoor air quality.

In 2016, Singer et al. conducted a field study examining how often exhaust fan operation in 16 airtight apartments in Northern California heated by gravity wall furnaces coincided with depressurization-induced downdrafting and spillage. The team monitored the frequency of coincident fan use and depressurization-induced furnace spillage. A diagnostic test found that most wall furnaces spilled combustion products when the apartments were set to have all exhaust fans operating at high settings. Additionally, downdrafting during exhaust fan use occurred in all apartments with sufficient data. The study, however, recognized the complexity and potential biases inherent in these tests and recommended further research into spillage and downdrafting from wall furnaces.

Fischer et al. (2018) measured methane (CH_4) and carbon dioxide (CO_2) emissions from natural gas appliances in 75 California homes, graphed their distributions, and extrapolated the results to the state level by combining Bayesian Markov Chain Monte Carlo sampling with state-level housing statistics. They found that, while changes in CH_4 emissions relative to changes in CO_2 emissions during furnace heating were lower than those for water heating and cooking, the pilot lights in furnaces—including wall furnaces—yielded higher levels of that relative change. The study suggests that inspections, gas leak repairs, checks for unlit pilot flames, and improvements in appliance ignition and combustion efficiency are effective means

[2] The Wobbe Number (or Wobbe Index) is a key measure of the interchangeability of fuel gases. It helps determine if a different fuel gas can be used in a burner without causing equipment issues.
[3] Annual Fuel Utilization Efficiency (AFUE) is a metric that expresses furnace energy efficiency. It is expressed as a percentage and indicates the fraction of the fuel used that is converted into heating.

of reducing emissions in residential buildings.

The Gas Technology Institute (GTI), in a research project that parallels this study (Gartland et al., 2023), evaluated the performance of 10 advanced retrofit wall furnaces that replaced low-efficiency baseline units in California homes. The retrofit models eliminated standing pilots and featured fan-type or direct-vent condensing technologies. The data showed that the retrofit furnaces operated for 37% fewer hours and used 68% less natural gas, resulting in an average annual utility bill reduction of $148. Emissions were also drastically curtailed, achieving 87% reductions in CO, 86% in NOx, and 93% in total hydrocarbons. They also found that while retrofit furnaces lowered indoor pollutant levels when actively running, indoor air quality was better with the baseline furnaces when the units were off, possibly because the old-standing pilots removed "indoor pollution by pulling in some room air for combustion."[4] Despite the energy and emission benefits, the project noted several operational issues with the retrofits, including excessive fan noise, failures with self-charging batteries on some models, and thermostat control complaints.

This report describes the fieldwork we conducted with 11 households in California with DHE. We metered heater usage and other indoor parameters of 12 low-efficiency DHE[5] over one heating season. Then we replaced 10 of those units[6] with high-efficiency models, and measured the usage of the new heaters and the same indoor parameters over the following heating seasons.

The report is part of the deliverables of the technical task "Task 3: Laboratory and Field Evaluation" of the California Energy Commission (CEC)-funded project "Cost-Effective Technologies and Strategies to Improve Energy Efficiency and Reduce Emissions of Direct Heating Equipment in California with Health Benefits" (Grant Agreement No. PIR-18-006, signed in October 2019). The goal of the task is to "obtain empirical data on current DHE energy use, size appropriateness, emissions, and indoor air quality and thermal comfort of households where they are used." (Grant Agreement PIR-18-006). The task includes, among other technical activities, selecting and recruiting households in California with low-efficiency DHE for field evaluations; evaluating the existing DHE units in those households; replacing the low-efficiency units with high-efficiency models; evaluating the new high-efficiency units; and assessing potential improvements in high-efficiency DHE technology and installation practices.[7] The report aligns with California state legislation's goals to reduce natural gas use in buildings.

The report proceeds as follows. Chapter 2 describes the fieldwork methodology, including the fieldwork approach and considerations for data analysis. Chapters 3 to 5 present and discuss, respectively, DHE usage and energy consumption, and changes in the indoor thermal

[4] Note that this could have also been possible due to increased ventilation during the non-heating season.
[5] One of the households had two DHE units.
[6] We replaced only one unit per household. One of the households selected for the study was heated by a floor furnace. There are currently no high-efficiency floor furnaces on the market. Therefore, the unit in that household was not replaced.
[7] Blum et al. (2024b) present and discuss results from the laboratory evaluations, which are also part of the technical task. The report includes estimates of emissions from the low- and high-efficiency units involved in the fieldwork.

environment and pollutant concentrations. Chapter 6 presents households' perspectives about high-efficiency DHE and discusses potential improvements in high-efficiency DHE technology and installation practices. Finally, Chapter 7 concludes with our main findings, their limitations, and directions for future research.

2. Methodology

2.1. Fieldwork Approach

We selected 11 households to participate in the fieldwork. The selected participating households (sites) represent: (a) diverse regions and varied heating requirements in the state; (b) different building types, including single-family detached houses and a multi-family building; and (c) various types of DHE. Figure 2 shows the location of the 11 sites. Table 1 presents the main characteristics of the participating households and their former DHE unit.

Figure 2. Location of the Participating Households

Note: According to the California Air Resources Board, the participating households in Oakland, Sacramento, and Stockton are located in disadvantaged and low-income communities.[8]

The fieldwork began with an initial visit to each site, during which we installed the metering devices. These devices monitored heater activity and recorded supply and return temperatures. They further measured temperature, relative humidity, and pollutant concentrations, as well as door and window closure in various spaces in the home. In addition, in some homes, the monitoring devices recorded the operation of ceiling fans and exhaust fans. Table 2 lists the spaces where we installed the monitoring devices and the parameters they measured.

[8] Disadvantaged communities are census tracts that rank in the top 25% of CalEnviroScreen 4.0. Low-income communities are census tracts with median household incomes at or below 80% of the statewide median income.

Table 1. Characteristics of Households and Existing DHE Units

Site		Building Type	Heated Space *sqft*	DHE Type	DHE Capacity *kBtu/hr*
DHE01	El Cerrito	SF	200	WF	20.0
DHE05	Oakland	SF	540	RH	20.0
DHE10	San Francisco	SF	400	RH	35.0
DHE11	San Francisco	SF	420	WF	35.0
DHE14	San Lorenzo	SF	800	WF2	50.0
DHE15	San Diego	SF	970	WF2	50.0
			450	WF	25.0
DHE16	Stockton	SF	360	WF	25.0
DHE18	Sacramento	MF	450	WF	Unknown
DHE19	Napa	SF	450	DV	14.0
DHE22	Arcata	SF	660	DV	30.0
DHEFF	Petaluma	SF	180	FF	35.0

Notes:

Building Type: SF: Single-family detached house; MF: Multi-family building (5+ units)

DHE Type: DV: Direct-vent; FF: Floor furnace; RH: Room heater; WF: Single-sided wall furnace; WF2: Double-sided wall furnace.

DHE18 Capacity: The unit had a painted nameplate; the manufacturer and capacity were unknown, but the unit was likely dated to the early 1950s, when the building was constructed.

During the initial visit, we also performed two one-time tests: a depressurization test and an air tightness test. The depressurization test evaluates the magnitude of negative pressure within a house, which can lead to downdrafts through combustion appliance vents and the spillage of combustion gases into living areas when appliance burners start operating. The test process includes operating all exhaust fans (dryer, bathroom, kitchen) and the furnace, with doors closed, to determine whether the pressure falls below critical thresholds. At all sites, the test indicated no significant pollutant spillage into the living space. The other one-time test, the infiltration test, measures a building's airtightness. The test uses a blower door device with a powerful, calibrated fan installed in an exterior doorway to depressurize the home. The test informs the potential to improve energy efficiency through air sealing. The test showed varying air infiltration rates[9] across the 11 sites, all indicating that the households would benefit from weatherization.[10]

[9] Infiltration rate is a measure of building airtightness. It refers to the rate at which outside air enters the building unintentionally, through leaks and openings in the building's envelope.

[10] Weatherization involves sealing gaps and cracks around doors, windows, and pipes, ensuring the home is properly insulated, repairing or replacing windows, and ensuring heating and air conditioning systems operate efficiently. We informed households on where to learn more about weatherization programs available in California.

Table 2: List of Parameters Measured by the Meters and Sensors Installed at Each Site

Where	Parameters
DHE unit	Fuel valve position Supply air temperature Return air temperature Combustion fan power Circulation fan power Total unit power
Direct-heated space	Temperature at different height levels[11] Indoor air quality Doors closure Windows closure Ceiling fan operation
Kitchen	Indoor air quality Exhaust fan operation Windows closure
Other space	Indoor air quality
Bathroom	Exhaust fan operation

Notes:

Other space refers to a bedroom or second living room, depending on the site.

The indoor air quality (IAQ) meters are assembled in an IAQ module, and collect the following data: temperature, relative humidity, and concentrations of CO_2, CO, optical particulate matter[12] ($PM_{2.5}$ and PM_{10}), and total volatile organic compounds (TVOC).[13]

Door and window closures, ceiling fans, and exhaust fans do not apply to all sites.

The fieldwork spanned three distinct heating seasons. The initial phase occurred during the winter of 2021–22, when we monitored the performance of existing low-efficiency units. Following the baseline data collection, in a second visit to the sites, we replaced the low-

[11] The team built a *stratification tree* to record temperatures at various heights. The device is a vertical structure equipped with temperature sensors positioned at four levels above the floor: 4", 24", 43", and 67".

[12] Optical particulate matter is measured using light scattering methods to detect airborne particles (PM). PM consists of a mix of solid particles and liquid droplets suspended in the air. PM is categorized by particle diameter: PM_{10} includes particles less than 10 microns, while $PM_{2.5}$ includes those smaller than 2.5 microns. Inhaling both types can negatively impact human health (https://ww2.arb.ca.gov/resources/inhalable-particulate-matter-and-health).

[13] Total Volatile Organic Compounds (TVOC) provides a single measurement that sums all Volatile Organic Compounds (VOCs) present in the air. VOCs are chemicals that easily vaporize and can cause a range of health effects. These compounds are found in many products, such as paint, varnish, wax, cleaning agents, cosmetics, and personal care items, and are released during their use. VOCs are also emitted during activities like frying or broiling food, smoking, and operating fuel-burning appliances (https://www.lung.org/blog/volatile-organic-compounds-at-home).

efficiency units with high-efficiency wall furnaces or direct-vent models.[14] Table 3 describes the characteristics of the DHE units removed from the sites and their replacements. Appendix A shows the old low-efficiency and new high-efficiency units. As a general rule, we replaced upright wall furnaces and direct-vent units with high-efficiency models of the same type as the former, low-efficiency unit. In addition, we replaced room heaters with a high-efficiency direct-vent model. The floor furnace was not replaced. All new models were sized based on each site's estimated heating load,[15] rounded up to the nearest available capacity of the replacement DHE type.

At three sites, the DHE replacement also involved changes to the heater's location or configuration. In DHE01, the old, low-efficiency upright wall furnace was oversized. The capacity we estimated for the new, high-efficiency DHE was available only in direct-vent models. We leveraged the fact that the old unit was already installed on an external wall to replace it with a lower-capacity direct-vent model. In DHE05, a low-efficiency room heater was installed near an unused fireplace in an internal wall of the living room, using the old fireplace's chimney for the heater's exhaust. Since the room heater was replaced with a high-efficiency direct-vent model, the new heater was installed on a different wall, an external wall in the same space. In DHE15, a low-efficiency double-sided wall furnace in use served primarily a living room and, secondarily, a children's playroom. Given that the unit was oversized, we replaced it with a lower-capacity, single-sided wall furnace facing the living room and a motorized rear outlet register embedded in the wall that blows warm air directly from inside the heater to the second heated space.

Once installed, the new, high-efficiency units were monitored over the subsequent two heating seasons: the winters of 2022–23 and 2023–24. After that period, during a third and final visit to the sites, we removed all metering devices and repaired any damage they might have caused to the house walls. We also conducted a brief survey among households, gathering their perspectives on how the new heater compares with the old one, how satisfied they were with the new heater, whether they noticed any changes to their gas bill after the new heater was installed, and their willingness to pay for a DHE like the new heater. Results from the survey are presented in Chapter 6 of this report.

[14] We also installed a new set of metering devices to measure electricity consumption by the new heaters, primarily for operating their combustion and convection (circulation) fans.

[15] We used the *Manual J* approach to estimate the heating load of each site. For more, please refer to Rutkowski (2016) or https://www.indeed.com/career-advice/career-development/manual-j-calculation.

Table 3: Low-Efficiency Existing Units and High-Efficiency Replacements

Site	Low-Efficiency Unit		High-Efficiency Unit	
	Model	**AFUE**	**Model**	**AFUE**
DHE01	Montgomery Ward SBI 9084	51.4%	Rinnai EX11CTN	81%
DHE05	Williams 2001622A	71.0%	Rinnai EX38CTN	80%
DHE10	Perfection Schwank VC235TN-W-1	64.0%	Rinnai EX38CTN	80%
DHE11	Williams 3509822	70.0%	Williams AC2030	82%
DHE14	Sears 600	75.0%	Williams AC3040	80%
DHE15	Williams C50D Williams 25GV-C-3T	65.1% 63.3%	Williams AC2030 Not replaced	82% -
DHE16	Williams 2509622	70.0%	Williams AC2030	82%
DHE18	(unknown)	(unknown)	Williams AC2030	82%
DHE19	Williams 14DV-3-NAT	62.4%	Rinnai EX22CTN	81%
DHE22	Williams 30DV-5	70.0%	Rinnai EX38CTN	80%
DHEFF	Custom-Aire G-35	55.0%	Not replaced	-

Notes:

All high-efficiency models are modulating furnaces. Modulating furnaces automatically and continuously regulate the amount of fuel used to maintain the home's desired temperature. This approach, unlike traditional single-stage gas furnaces, results in higher efficiency and lower operating expenses.

The AFUE of the existing double-sided unit was estimated using a similar model from the late 1980s and may therefore be overestimated. The second existing DHE unit in DHE15 was not replaced because the team replaced only one unit per site.

The existing unit in DHE18 had a painted nameplate, and the team could not identify its manufacturer, brand, model, capacity, or AFUE. It was likely produced in the 1950s by a company that no longer exists.[16]

The existing unit in DHEFF was not replaced because no high-efficiency floor furnace model was available on the market. Because the manufacturer no longer exists and the unit's nameplate does not list its AFUE, the AFUE was estimated using the typical AFUE for vintage floor furnaces.

2.2. Data Analysis

Once all field data were collected, organized, and validated, we analyzed heater usage, energy consumption, and changes in the indoor thermal environment and in pollutant concentrations during heater operation. All meters and sensors provided 30-second data.

We relied on data from the fuel valve position, combined with changes in supply air

[16] According to the building manager, the unit was installed in the early 1950s, when the building was built.

temperature, to determine whether the heater was on or off at each time step. We estimated total energy consumption from gas and electricity consumption. The gas consumption of the low-efficiency units was calculated at each time step when the heaters were on, based on their capacities. For the modulating, high-efficiency units, gas consumption was estimated at each time step when the heater was on, based on empirical curves[17] that associated the fuel valve position with the amount of gas used. Electricity use at each time step was directly measured.

Changes in indoor thermal conditions were analyzed using data from the four sensors in the stratification trees[11] and from the indoor air quality modules installed in the directly heated space and in two additional spaces at each site, which measured temperature and relative humidity. For changes in pollutant concentrations, we also relied on the data from the indoor air quality modules. One important aspect of these two analyses is how we assessed the effects that each DHE unit, low- and high-efficiency, had on the spaces directly and indirectly heated by these units.

Heaters often operate in short bursts. Assessing the effects of each short operating cycle separately can be misleading because those effects often overlap. Therefore, we introduced the concept of a *heating cycle*, the unit of time we used in our assessments. A heating cycle consists of a sequence of periods during which the heater is on, separated only by brief intervals when it is off. Hence, our definition of heating-cycle aggregates short burner cycles into intervals during which it is clear that the heater was used to achieve and maintain warmth in the space. These intervals were separated by relatively long periods when the heater was off. The average heating cycle duration across sites ranged from 4 to 78 minutes.

At each site, we determined the minimum heater inactivity period required to clearly distinguish individual heating cycles. This was established using the inverse of air changes per hour (ACH), known as the "residence time," which represents the average duration needed for all the air in a space to be fully replaced. The ACH values are from the blower door tests. By ensuring that heating cycles are separated by at least one residence time unit, we minimize the influence of a previous cycle on the subsequent one, as the indoor air is mostly exchanged before the next cycle begins.

In addition, all our analyses of DHE impacts on the indoor environment are relative to the indoor condition at *time zero*, the beginning of each heating cycle. They correspond to the indoor condition at the start of the first short DHE operating cycle of each heating cycle.

[17] The empirical curves were derived for each high-efficiency unit.

3. Heater Usage and Energy Consumption

We analyzed the natural gas consumption of both low- and high-efficiency DHE units at each site. Gas usage is influenced by several factors, some of which may have varied across the seasons during which we measured consumption for each unit type. The first factor is the thermal properties of the household building envelope.[18] The second factor is seasonal weather conditions, represented by total heating degree days[19] (HDD) and the specific HDD values on days when occupants used the DHE. The third set of factors relates to household occupancy and practices and includes the number of occupants, the use of windows and doors (open/closed), residents' daily routines, and their heating-related choices, such as thermostat settings and whether the heater is used at all. Table 4 and Table 5 summarize the weather conditions, operating hours, and energy consumption during the periods when the low-efficiency and high-efficiency units were assessed.[20]

As previously noted, directly comparing gas usage between low- and high-efficiency units is limited by the dynamic factors influencing DHE operation. To address this, we normalized gas consumption to HDD on days when the units were in use, providing a more accurate estimate of potential savings from replacements. Nevertheless, the energy consumption per HDD values reported in Table 4 and Table 5 reflect measurements taken under varying seasonal conditions and should be treated as approximate estimates of energy savings rather than precise measurements. Therefore, cross-unit (low- *versus* high-efficiency unit) and cross-site comparisons should be interpreted with caution.

At six sites, the natural gas energy consumption per HDD was lower with the high-efficiency unit than with the low-efficiency unit. Specifically, at five sites (DHE01, DHE10, DHE11, DHE15, and DHE19), the ratio of natural gas energy consumed per HDD with the high-efficiency unit relative to the low-efficiency unit ranged from 60% to 80%. This means the high-efficiency unit used 60% to 80% as much energy per HDD as the low-efficiency unit. At one site (DHE18)—where the low-efficiency unit likely dated from the 1950s—that ratio was around 20%, indicating a much larger decrease in gas energy consumption per HDD. Conversely, at four sites (DHE05, DHE14, DHE16, and DHE22), the high-efficiency unit used more gas per HDD than the low-efficiency unit. Notably, these sites experienced lower average HDD during high-efficiency operation, which, under constant conditions, would typically lead to reduced gas consumption. Instead, the high-efficiency units consumed more gas, suggesting that weather

[18] The building envelope serves as the barrier between a home's interior and the outside environment, enclosing all conditioned spaces. It consists of structural elements such as walls, roofs, floors, windows, and doors. The envelope's thermal characteristics determine how effectively it controls heat flow between indoors and outdoors. Important factors include the level of insulation, the degree of airtightness, and the specific thermal properties of each component.

[19] A heating degree day is a standard measure for estimating the energy needed to heat a building. It is calculated by subtracting the daily average temperature from a reference temperature, usually 65°F. Higher HDD values indicate greater heating demand. For additional information, visit the EIA's website: https://www.eia.gov/energyexplained/units-and-calculators/degree-days.php.

[20] Note that the status of the relevant windows and doors was basically the same across heating cycles of low- and high-efficiency unit operation, and did not statistically significantly affect heater energy use estimates.

alone does not account for this increase. The likely explanation involves shifts in household heating behavior and/or a household-specific “rebound effect,” in which increased efficiency leads to greater use. The rebound may be linked to improved temperature control from new thermostats and heat modulation features, leading to more frequent or longer operation. At DHE16, although the high-efficiency unit operated for fewer hours, the data show that the average temperature during its operation was approximately 4°F higher than during the low-efficiency unit's operation, suggesting a change in thermal needs. At the other three sites, longer operating hours indicate increased DHE use. Also, in two of these sites, the average temperatures during high-efficiency operation were approximately 6°F (DHE05) and 10°F (DHE14) higher than during low-efficiency operation. Ultimately, although energy use increased at these four sites, the rebound effect enhanced participants' thermal comfort, thereby providing household comfort benefits.

Table 4: Low-Efficiency Units Operating Conditions and Energy Consumption

Site	Average Daily HDD		Operating Hours	Natural Gas		Electricity
	Season	Days On		Total	Per HDD	Total
			hours	*MMBtu*	*kBtu*	*kWh*
DHE01	11.2	10.5	390	7.8	3.8	-
DHE05	11.2	6.9	166	3.3	1.6	-
DHE10	10.4	5.1	59	2.1	1.1	-
DHE11	10.4	9.1	289	10.1	5.4	1.2
DHE14	10.6	2.7	12	0.6	0.3	3.6
DHE15	6.6	1.7	40	2.0	1.7	-
DHE16	13.0	12.6	698	17.5	7.4	-
DHE18	13.3	10.2	608	25.5	10.5	-
DHE19	14.0	13.4	579	8.1	3.2	-
DHE22	16.6	11.3	126	3.8	1.3	-
DHEFF	14.6	14.1	531	18.6	7.0	-

Notes:

All values refer to the heating season from October 2021 through March 2022.

The columns “Days On” and “Per HDD” refer only to the days when the DHE unit was in use.

The operating hours are the total time during which the heater was on, measured in minutes, converted to hours, and rounded to the nearest integer.

Only the low-efficiency units in DHE11 and DHE14 had a circulation fan. The one in DHE14 was integrated into the unit, while the one in DHE11 was an external accessory.

Total energy consumption comparisons between low- and high-efficiency units must also account for the electricity used by the high-efficiency models, which all feature circulation and combustion fans.[21] These fans accounted for just 0.1% to 0.9% of the season's total equivalent natural gas energy, making their additional energy use negligible in the overall heating context. Among the 11 participating sites, only DHE11 and DHE14 had low-efficiency units with fans. Notably, the high-efficiency unit at DHE11 used more electricity than its low-efficiency counterpart, whereas at DHE14, the opposite was true. This makes direct comparisons difficult and potentially misleading. Unlike the automatically controlled fans in high-efficiency units, which run whenever the unit operates, the fans in low-efficiency units were manually operated. As a result, these fans may not always have been active during DHE operation, or may have been running when the heater was off.

Table 5: High-Efficiency Units Operating Conditions and Energy Consumption

Site	Average Daily HDD		Operating Hours	Natural Gas		Electricity
	Season	Days On		Total	Per HDD	Total
			hours	*MMBtu*	*kBtu*	*kWh*
DHE01	11.7	11.3	826	5.2	2.5	13.0
DHE05	11.7	9.7	266	6.9	3.2	15.4
DHE10	10.2	10.6	102	2.6	1.2	5.8
DHE11	10.2	8.3	261	6.9	3.7	3.4
DHE14	11.0	2.7	34	1.3	0.7	1.7
DHE15	7.9	5.7	163	5.2	3.6	1.7
DHE16	12.8	12.0	607	18.9	8.1	7.5
DHE18	13.2	7.8	130	3.7	1.6	1.3
DHE19	13.2	11.3	397	5.5	2.3	14.6
DHE22	16.3	15.6	496	11.0	3.7	28.2

Notes:

All values are averages of measurements taken over two heating seasons: October 2022 to March 2023 and October 2023 to March 2024.

The operating hours are the total time during which the heater was on, measured in minutes, converted to hours, and rounded to the nearest integer.

The columns "Days On" and "Per HDD" refer only to the days when the DHE unit was in use.

[21] Both fans are integrated into the unit. The circulation fan distributes heated air efficiently throughout the space, while the combustion fan supplies air required for combustion and expels the resulting gases through the vent system. Together, these fans enhance the unit's heating performance and ensure safe operation.

Although the circulation fans in all high-efficiency models slightly increase total energy use, they were expected to improve users' thermal comfort. This is confirmed from the participating households' impressions of the new heaters, as expressed in the survey we conducted at the end of the monitoring period described in Section 6.1. In addition, Chapter 4 presents and discusses changes in indoor temperature associated with the low- and high-efficiency models.

4. Changes in Indoor Thermal Conditions

Across all monitored sites, heater use consistently improved indoor thermal conditions, as measured by the temperature and relative humidity sensors in the direct-heated space and in select interior living spaces, following the onset of each heating cycle (time zero).[22] The field data show that the high-efficiency units delivered a significantly faster thermal response and, sometimes, a higher steady-state temperature plateau than the low-efficiency units. Upon system activation, the high-efficiency units exhibit a steeper rate of temperature increase, bringing the direct-heated space to preferred higher temperatures in a fraction of the time. Conversely, the low-efficiency units exhibit a sluggish thermal response, taking substantially longer to heat the space and failing to reach the same elevated average temperatures due to passive, buoyancy-driven air distribution and the performance of system components. In addition, the data show a direct correlation between the high-efficiency unit's fast heating capability and the accelerated reduction of indoor moisture. As the high-efficiency units quickly raise the dry-bulb temperature, local relative humidity drops sharply.[23] In comparison, the low-efficiency units' slow heat delivery results in a prolonged, gradual, and lower decline in relative humidity.

Figure 3 and Figure 4 provide an overall perspective on changes in the thermal environment conditions of the direct-heated space, based on average temperature and relative humidity, respectively, across all heating cycles for the low- and high-efficiency units at all sites.[24] The plots in each figure are grouped by the initial conditions (temperature and relative humidity) of each cycle. The figures show that, when comparing the effects of heating cycles with similar starting conditions on indoor thermal conditions across sites, the high-efficiency units, on average, increased the temperature by up to 10°F and reduced the relative humidity by up to 17%, while the low-efficiency units increased the temperature by up to 5°F and had an almost negligible reduction in relative humidity.

The temporal dynamics of heating varied substantially across sites. Some homes exhibited rapid temperature increases immediately after heater activation, with steep rises during the first several minutes before stabilizing. Other sites exhibited slower warming responses, with temperatures increasing gradually throughout the heating cycle before reaching a plateau. Despite differences in heating rate, the vertical thermal stratification[25] pattern in the direct-heated space remained consistent across sites.

[22] These sensors are the ones embedded in the IAQ modules.
[23] Suppressing excess relative humidity at a faster rate rapidly eliminates the 'cold and clammy' conditions associated with slow-warming systems.
[24] The shaded areas correspond to the 95% confidence interval for the average and reflect the variations in heating cycles across all sites. The average values are biased towards results from sites with more cycles.
[25] Vertical thermal stratification is a condition where indoor air forms distinct, temperature-regulated horizontal layers, resulting in a large temperature difference between the floor and the ceiling.

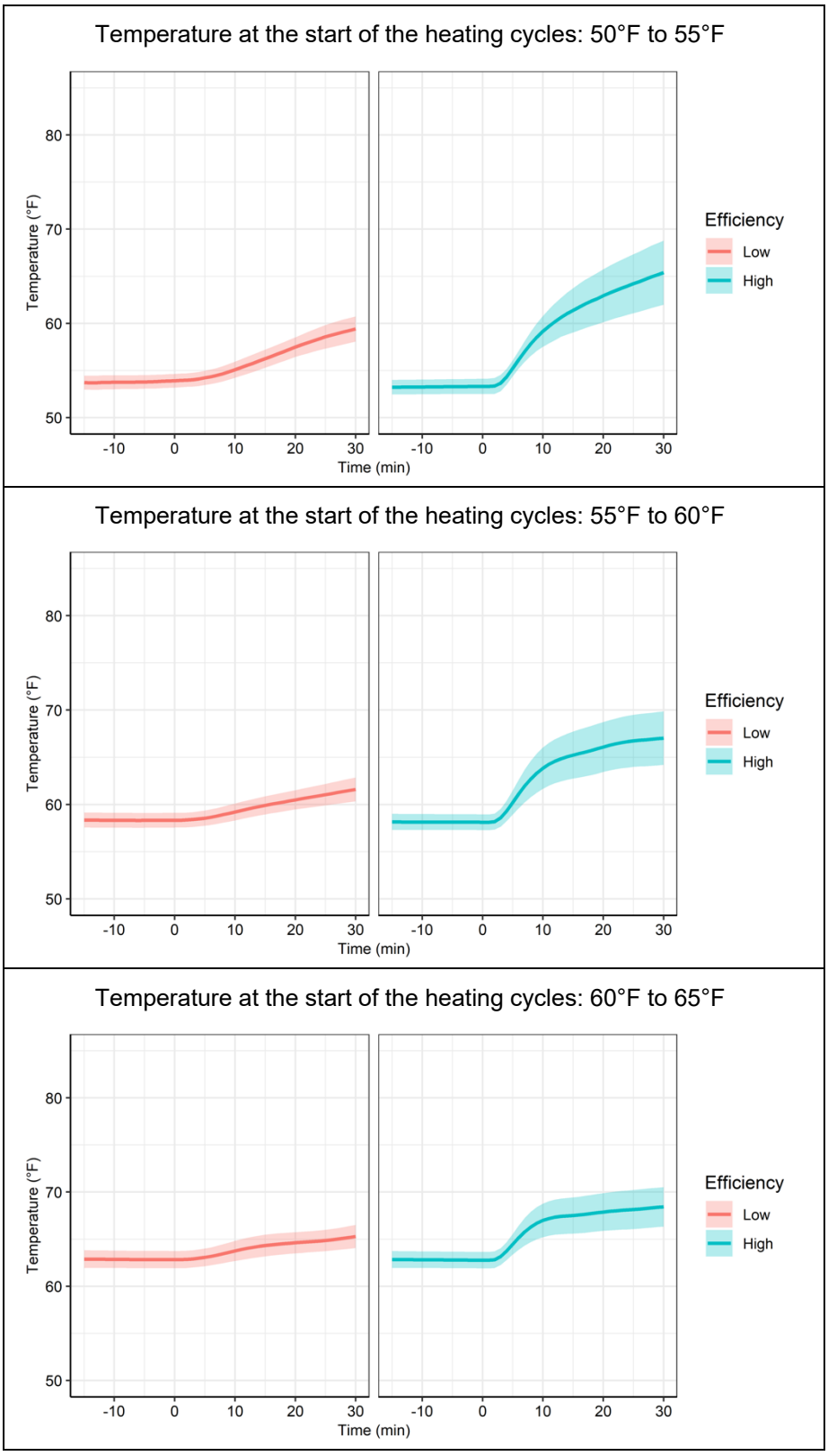

Figure 3. Temperature in the Direct-Heated Space Over Time

Time=0 refers to the heating cycles' time zero, the start of the heater operation.

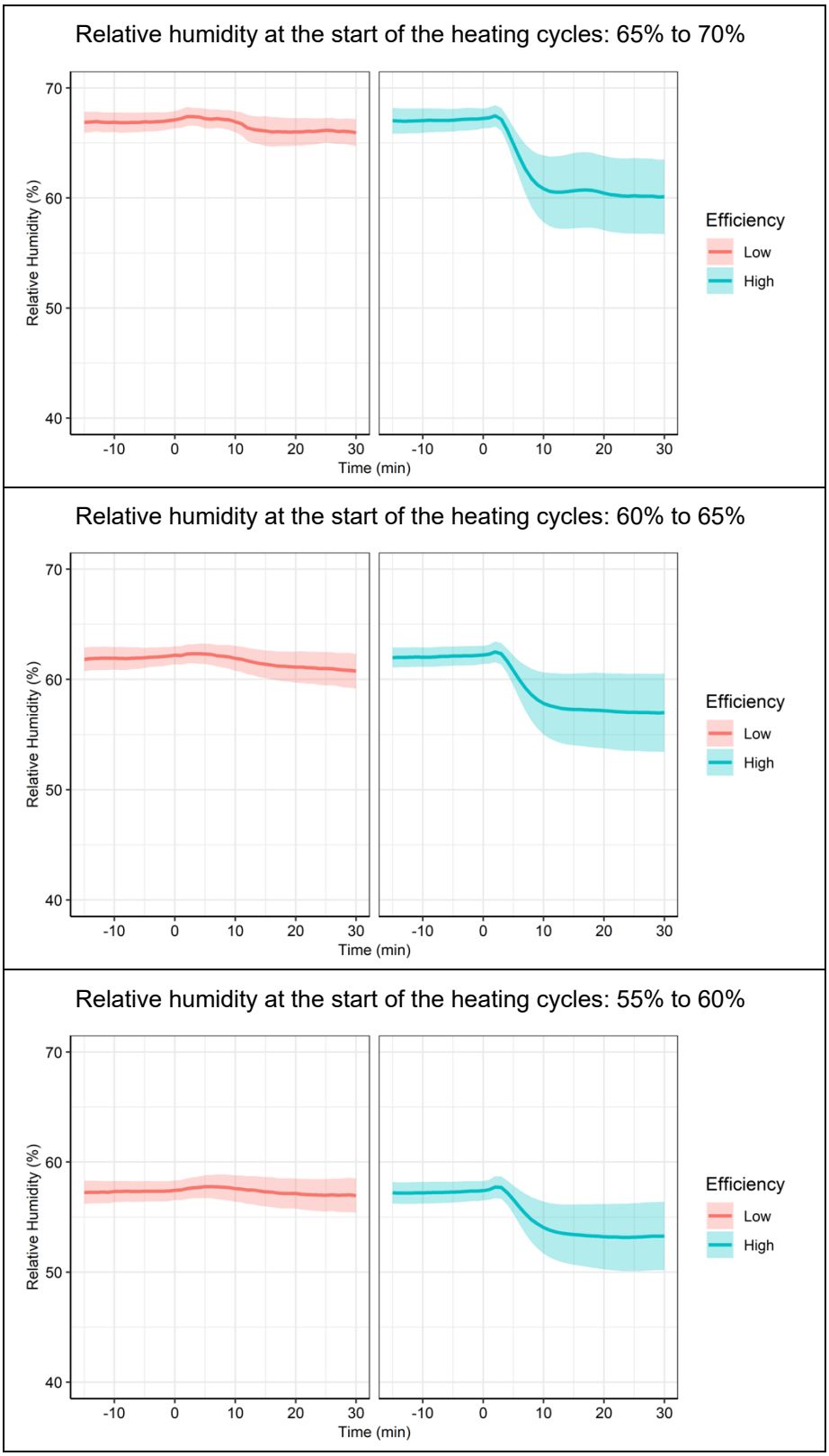

Figure 4. Relative Humidity in the Direct-Heated Space Over Time

Time=0 refers to the heating cycles' time zero, the start of the heater operation.

Data from the air temperature sensors installed on the stratification trees in the direct-heated space show that temperature increases were largest near the upper stratification sensors and decreased progressively with sensor height, indicating vertical thermal stratification during heater operation. Figure 5 compares the temperature stratification during the operation of the low- and high-efficiency units across all sites.[24] Because the starting temperatures of the heating cycles were not always the same, comparisons were grouped by the initial temperature of each heating cycle for comparability.

Clear differences in temperature distributions between the low- and high-efficiency units were observed, highlighting the better performance of the latter. Overall, the low-efficiency units recorded closer (clustering of) temperatures among the three lowest sensors on the stratification tree, compared with the high-efficiency systems, where the temperatures across all sensors are more evenly distributed, with the second and third highest located sensors having temperatures closer to the highest sensor on the tree. Given a coldest-startup baseline of 50°F to 55°F, the initial 10-minute ramp rate at 67-inch head height is a critical indicator of system responsiveness. For the low-efficiency gravity unit, the temperature at this height slowly increases from a baseline of approximately 53°F to approximately 58°F by the 10-minute mark, at a rate of roughly 0.5°F per minute. In contrast, the high-efficiency unit rapidly raises the temperature to 67°F within the same 10-minute window, achieving a steeper temperature increase rate of around 1.4°F per minute. This means the fan-forced, high-efficiency units deliver heating 3 times faster than their gravity-driven counterparts during the initial warm-up phase, helping to quickly bring the indoor temperature to the desired level.

The presence of a convection fan in the high-efficiency units mechanically overcomes natural buoyancy and reduces vertical temperature stratification. Thirty minutes after firing the low-efficiency unit with gravity heating, temperatures at the stratification tree show significant thermal gradients: the 67-inch height reaches 69°F, while the 24-inch height lags far behind at 58°F, resulting in an uncomfortable 11°F difference within the primary living zone. By contrast, the high-efficiency unit with a convection fan achieves more uniform hot-air distribution, resulting in closer temperature readings at the 24-inch, 43-inch, and 67-inch sensors. After 30 minutes of operation, the high-efficiency unit records a 67-inch temperature of 73°F and a 24-inch temperature of 66°F, reducing the stratification to 7°F. This narrowing represents a 36% reduction in vertical thermal stratification between the low- and high-efficiency units, shifting the indoor thermal condition much closer to a uniform, more comfortable environment.

Further, floor-level data emphasize the lower performance of low-efficiency passive gravity units compared to high-efficiency units with fans. Under the low-efficiency unit, the temperature at the 10-inch ankle-height sensor remained very low, averaging 54°F even after 30 full minutes of continuous heater operation. The gravity heating units lack the capability to force the laminar warm-air flow down to the floor, leaving occupants with cold feet despite a much warmer temperature at the higher level (head and above). The high-efficiency unit's fan was able to force a steady, mechanically circulated air flow that pulls the temperature at the lowest level upward, away from the baseline. This trend holds across all three startup temperature groups, demonstrating that high-efficiency DHE can deliver a more uniform indoor climate.

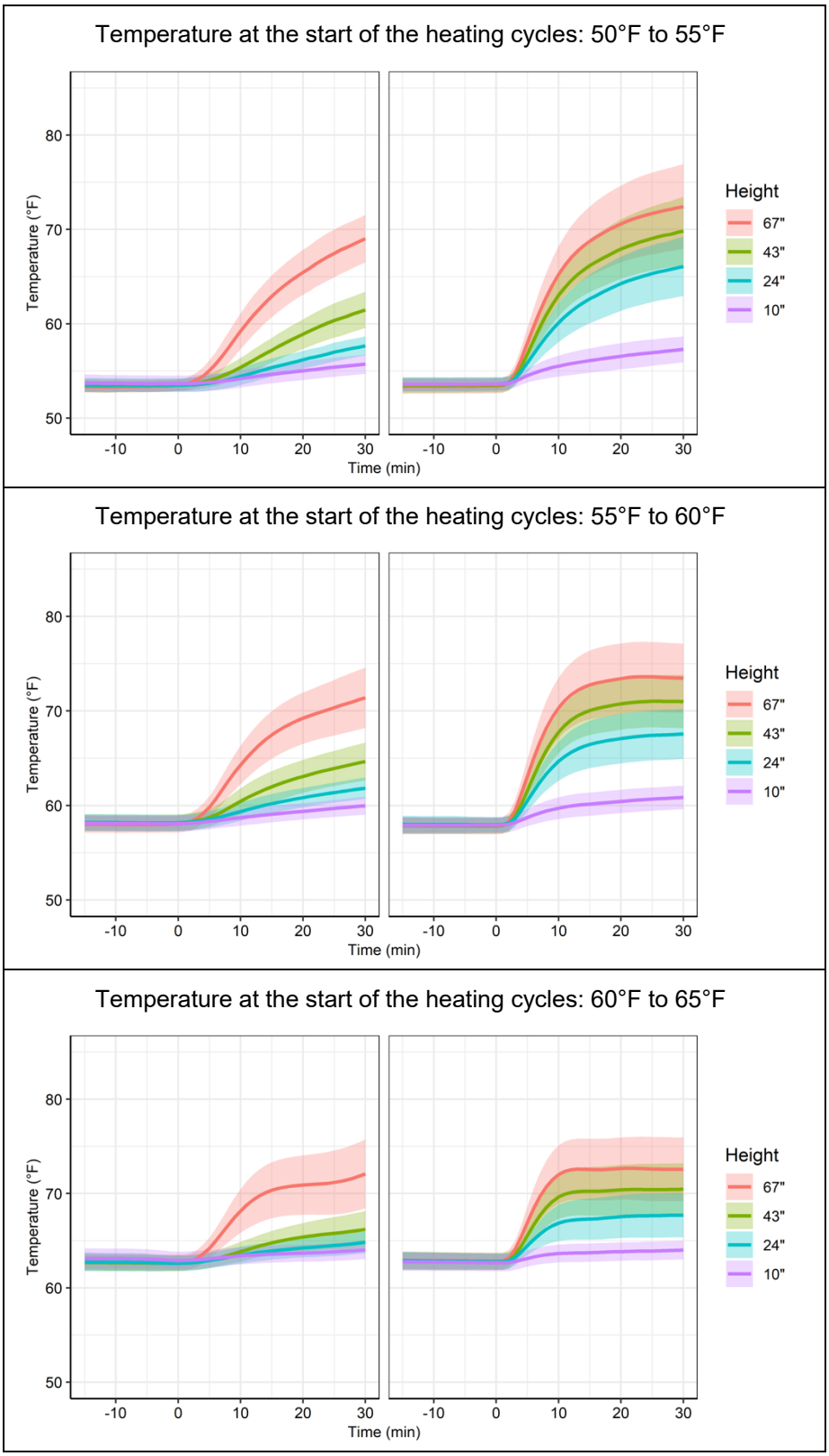

Figure 5. Temperature Over Time at Different Heights of the Stratification Tree

Time=0 refers to the heating cycles' time zero, the start of the heater operation.

Within the interior spaces, the directly heated room consistently experienced the largest temperature increase, typically warming by approximately 3–9°F across sites. Adjacent rooms, such as kitchens and bedrooms, warmed more gradually and experienced smaller increases of approximately 1–6°F. Relative humidity changes were comparatively small and generally decreased during heater operation, typically by approximately 3 to 6 percentage points in the direct-heated space. Differences between low- and high-efficiency units were less pronounced but still detectable. The directly heated room was often warmed by approximately 1°F to 3°F more with high-efficiency units than with low-efficiency units.[26] Adjacent rooms showed similar but smaller differences. Appendix B shows the average absolute and relative changes in temperature and relative humidity for the low- and high-efficiency units across all sites.

Although the magnitude of the efficiency-related differences varied between sites, the overall trend was consistent: high-efficiency units generally produced faster warming and slightly higher peak temperatures throughout the sensor array. This is consistent with the participating households' impressions of the new heaters, as expressed in the survey we conducted at the end of the monitoring period, described in Section 6.1.

4.1. High-Efficiency DHE Performance Across Sites

While the overall heating pattern was consistent across sites, we observed considerable variability in both the magnitude and timing of temperature responses of the high-efficiency units.[27] Some homes exhibited extremely rapid heating responses immediately after heater activation, while others warmed more gradually throughout the heating cycle. Sites such as DHE05, DHE10, DHE16, DHE18, DHE19, DHE22, and DHEFF showed particularly rapid temperature increases following heater activation, with steep initial rises in the stratification tree sensors and large peak increases later in the heating cycle. In contrast, sites such as DHE01, DHE11, DHE14, and DHE15 exhibited slower warming responses, with temperatures rising more gradually before reaching a plateau.

Despite these differences in heating rate, all sites displayed a consistent vertical temperature gradient within the stratification tree. Higher sensors experienced the largest temperature increases, while lower sensors showed progressively smaller changes. The spatial distribution of heating within the home was also consistent across sites, with the primary heated room experiencing the largest temperature increase and adjacent spaces warming more slowly. Specific comments on each monitored site are provided below the figures in Appendix A.

At DHE01, heater activation led to a relatively rapid increase in temperature within the stratification tree. Temperatures changed shortly after time zero and then stabilized quickly

[26] This could mean that either the low-efficiency units were never able to reach the thermostat's set point or that households set the thermostats on the high-efficiency units to higher temperatures than those on the low-efficiency units.

[27] Note that variability across sites is due not only to differences in the climatic characteristics of the site but also to the building envelope, home floor plans, the location of the heater in the home, the location of sensors relative to the heaters, and thermostat settings.

during the heating cycle. The upper stratification sensor increased by approximately 3°F with the high-efficiency unit within an average cycle duration of approximately 5 minutes. Within the home, the directly heated space was warmed by approximately 3°F during heater operation. The kitchen experienced almost no change in temperature.[28] Relative humidity declined modestly (by less than 3% Rh) during the heating cycle in the heated space.

DHE05 exhibited one of the strongest heating responses among the monitored homes. Temperatures within the stratification tree increased rapidly following heater activation, with steep increases during the early portion of the heating cycles, which averaged about 18 minutes. The upper sensor increased by approximately 17–19°F with the high-efficiency unit. The directly heated space warmed by approximately 9°F, while adjacent rooms experienced smaller increases of approximately 1°F (bedroom) to 5°F (kitchen). Relative humidity decreased by about 10% Rh in the direct-heated space and by 1–6% Rh in other adjacent spaces during heating.

At DHE10, temperatures increased sharply after heater activation, then quickly dropped and plateaued later in the heating cycle. The temperature at the highest sensor reached a peak increase of approximately 13°F within an average cycle time of about 4 minutes, then stabilized at about 8°F increase from the start of system activation. Temperature in the directly heated space followed the same pattern, while other adjacent rooms were seemingly almost unaffected. The reverse pattern was observed for relative humidity, with a decrease of almost 9% Rh in the direct-heated space, followed by a stabilization at a 6% Rh decline soon after the heater stopped operating.

At DHE11, temperature increases occurred more gradually than at several other sites. The upper stratification sensor increased by approximately 11°F to 13°F, while the mid-height sensor increased by approximately 9–10°F. Lower sensors showed increases of approximately 1–3°F during the average heating cycles of approximately 48 minutes. Interior spaces warmed by approximately 5°F in the direct-heated room and by roughly 3–4°F in adjacent rooms. The effect on relative humidity is limited to a decline of less than 5% Rh across all spaces.

Heating behavior at DHE14 showed a gradual yet consistent temperature increase after heater activation during a long heating cycle of almost 80 minutes. The upper stratification sensor increased by approximately 20°F, while the medium and lower sensors increased by approximately 5–10°F, depending on height. Unlike other sites, the interior spaces warmed almost consistently, indicating well-distributed air, with temperatures increasing by approximately 8–10°F across all spaces. Conversely, the relative humidity declined at similar rates, resulting in a 5–7% drop in Rh across all spaces.

Similarly, DHE15 exhibited one of the more gradual heating responses among the monitored homes. Temperature increases occurred slowly following heater activation and reached a plateau later in the heating cycle, which averaged about 52 minutes. The upper sensor

[28] In DHE01, while the direct-heated space is a study on the second floor of the house, the kitchen is on the first floor.

increased by approximately 7°F over this time, and the interior spaces warmed at the same rate, while the relative humidity in the directly heated space declined by about 5% Rh.

Temperature increases at DHE16 occurred rapidly within the averaged 18-minute cycles. The upper-stratification sensor increased by approximately 20°F, while mid- and low-height sensors showed only minor increases (up to 2°F), suggesting pronounced thermal stratification. The heated room warmed by approximately 4°F, while the other rooms received negligible heat. Relative humidity in the direct-heated space was moderately affected by a modest 3% Rh decline.

At DHE18, the temperature quickly rose by almost 15°F within the average cycle time of 12 minutes. However, as soon as the heater stopped operating, the space quickly lost the heat generated at almost the same rate. A similar trend, but of smaller magnitude, was observed in the room temperatures measured in the direct-heated space and across all adjacent spaces. Correspondingly, relative humidity decreased by about 5% Rh, then gradually increased after the heater stopped.

DHE19 exhibited relatively rapid heating following heater activation for about 12 minutes. The upper-stratification sensor increased by approximately 12°F, while mid-height sensors followed this change more closely, increasing by approximately 8-12°F, suggesting less thermal stratification at this site. The heated room and the adjacent spaces warmed by approximately 4-6°F during the heating cycle.

DHE22's heater exhibited a rapid temperature rise during the 4-minute average cycle duration, increasing by about 5°F. Despite the relatively small temperature changes compared to other sites, thermal stratification was less problematic, as indicated by the comparable temperature variations at other middle-height sensors. Temperatures measured across different spaces also indicated similar temperature profiles, suggesting a relatively well-mixed air at this site. Relative humidity declined by about 3-5% Rh across different rooms.

Regarding the low-efficiency floor furnace unit at DHEFF, the heating cycles produced temperature responses similar to DHE18, with the temperature rising quickly when the heater started but falling as soon as the heater turned off. The average operation time was about 13 minutes for this system, during which the temperature at the top sensor increased by about 11°F, with moderate thermal stratification. The temperature trend was observed in the direct-heated room, but was much less pronounced in the adjacent spaces. The trend in relative humidity mirrored this impact, but in the opposite direction: the humidity dropped by about 4% Rh in the heated space and had no effect in all other rooms.

5. Changes in Pollutant Concentrations

Overall, the field data suggest that in some cases, heater operation may have increased the indoor concentrations of certain pollutants, particularly CO_2 and CO. The data also indicate that, in general, concentrations of these two pollutants are lower during operation of high-efficiency units than during operation of low-efficiency units. Despite increases in pollutant concentrations during heater operation, we did not observe any critical exposure levels under regular operating conditions. Figure 6 and Figure 7 show average pollutant concentrations before and during heater operation across all sites.[24] The figures also indicate a large variability across sites and heating cycles.

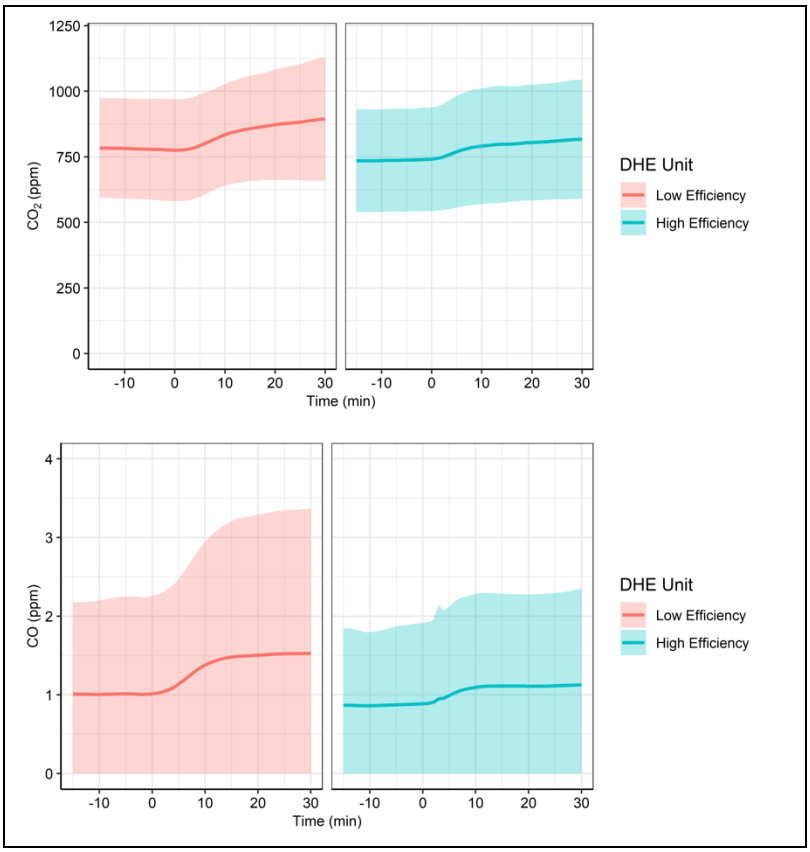

Figure 6. CO_2 and CO Concentrations in the Direct-Heated Space During Heating Cycles

Time=0 refers to the heating cycles' time zero.

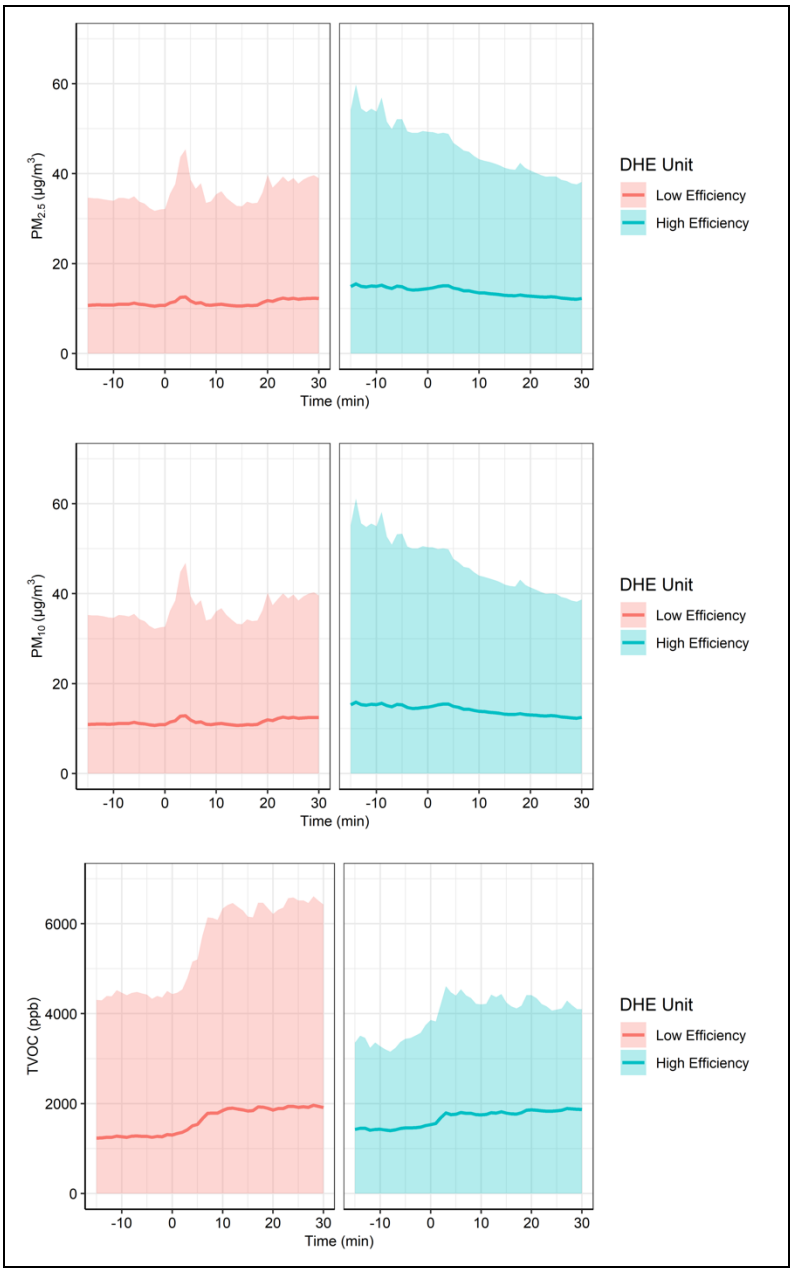

Figure 7. PM and TVOC Concentrations in the Direct-Heated Space During Heating Cycles

Time=0 refers to the heating cycles' time zero.

5.1. Carbon Dioxide (CO_2)

Metabolic processes and combustion of fossil fuels produce CO_2. The average atmospheric CO_2 concentration is around 430 ppm (NOAA, 2025), though it can vary significantly over time and across locations. Indoor CO_2 concentrations are typically higher than those outdoors. In poorly ventilated rooms, CO_2 levels can exceed 5,400 mg/m³ (about 3,000 ppm) solely due to human metabolism (Canada, 1987). An indoor CO_2 concentration below 1,000 ppm has been historically viewed as an indicator of acceptable indoor air quality (ASHRAE, 2025).

Table 6 presents medians and interquartile ranges (IQR) of CO_2 concentrations in the direct-heated space for low- and high-efficiency units across all sites. The values are reported in 5-minute intervals, from 15 minutes before the start of heating cycles through the first 30 minutes of the cycles. Concentrations increase after the low-efficiency units start in DHE05, DHE14, DHE19, DHE22, and DHEFF, a pattern not observed during the operation of the high-efficiency units at these sites (except DHEFF, where no high-efficiency unit was installed). In DHE10, the median CO_2 concentration increased by 122 ppm during the operation of the high-efficiency unit, compared with 100 ppm during the operation of the low-efficiency unit. For all other sites, no relevant changes in CO_2 concentration are observed after the heaters start.

Human emissions and ventilation typically account for almost all of the variation in indoor CO_2 concentrations. The differences in CO_2 concentrations between heater-on and heater-off conditions, for example, may have been driven by higher occupancy of the direct-heated space during heater operation than during heater-off periods. However, assuming no changes in household behavior after heater replacement, occupancy of the direct-heated space would not explain cases in which no additional concentration was observed during operation of the high-efficiency heater compared with the low-efficiency unit. We, therefore, do not rule out the possibility that the heaters have affected the CO_2 concentration in the direct-heated space. At the sites listed above, where CO_2 concentrations increased during the low-efficiency units' operation but not during the high-efficiency units' operation, the concentration changes suggest exhaust gas spillage into the living space while the vent is being heated.[29] The combustion fans in the high-efficiency units establish draft either before or at the start of burner operation, which should have prevented that spillage. In addition, the forced ventilation provided by the high-efficiency units' convection fans could have helped mitigate the effect of any CO_2 source (including, potentially, the new heater) on the sensor, masking any real changes in concentration. Besides all these factors that may explain variations in CO_2 concentrations, variability in measurements across sites can be attributed to household behavior and to the location of sensors relative to the heater and other potential CO_2 sources, such as gas cooking appliances without effective kitchen ventilation.

During heater operation, median CO_2 concentrations across all sites ranged from 505 ppm to 1581 ppm (DHE14) for low-efficiency units and from 548 ppm to 1319 ppm (DHE10) for high-efficiency units. In Table 6, the large IQRs for some sites, particularly DHE19 and DHE22,

[29] Note that, despite our initial spillage test not showing any spillage from the low-efficiency units, the same process was observed on these sites for changes in CO concentrations (Section 5.2).

indicate substantial fluctuations in CO_2 levels, suggesting that intermittent sources, such as human activity or changes in ventilation, likely contributed to these variations. Because occupants' behavior and other factors can significantly affect CO_2 concentration levels, the results above should be considered suggestive rather than definitive. Appendix C compares CO_2 concentration distributions in direct-heated spaces during both operation and non-operation periods for low- and high-efficiency units in all sites.

Table 6: CO_2 Concentration in the Direct-Heated Space

Site	**Time relative to heating cycle start** (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE01										
Low-efficiency										
Median	659	657	660	661	660	664	662	660	655	655
IQR	167	167	160	156	168	168	161	166	164	165
High-efficiency										
Median	564	564	562	562	560	558	559	558	560	560
IQR	136	135	138	137	139	145	146	144	143	146
DHE05										
Low-efficiency										
Median	590	590	586	587	627	825	955	1,019	1,085	1,149
IQR	199	198	198	190	185	165	180	178	190	197
High-efficiency										
Median	626	625	626	629	645	655	662	664	666	667
IQR	150	150	148	149	140	136	133	130	133	132
DHE10										
Low-efficiency										
Median	872	872	872	880	901	940	1,010	1,008	1,007	1,001
IQR	298	292	293	319	300	330	358	348	353	331
High-efficiency										
Median	1,086	1,082	1,094	1,106	1,197	1,245	1,254	1,281	1,295	1,319
IQR	514	504	469	482	512	614	582	617	735	731
DHE11										
Low-efficiency										
Median	681	686	690	698	703	708	709	708	707	701
IQR	272	274	278	275	258	256	248	243	230	221
High-efficiency										
Median	799	800	797	778	825	827	829	838	839	833
IQR	335	324	359	357	344	308	313	324	328	328
DHE14										
Low-efficiency										
Median	733	737	770	779	1,336	1,434	1,490	1,482	1,513	1,581
IQR	67	65	59	62	19	38	78	42	19	36
High-efficiency										
Median	522	507	513	513	548	583	613	629	627	673
IQR	176	151	133	160	165	164	168	170	213	218

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE15										
Low-efficiency										
Median	753	748	747	747	752	791	791	800	822	855
IQR	169	160	157	154	147	79	105	96	91	99
High-efficiency										
Median	577	576	570	580	585	612	616	631	655	667
IQR	195	209	214	214	231	236	229	250	246	248
DHE16										
Low-efficiency										
Median	842	837	830	810	807	808	808	797	794	787
IQR	238	225	211	226	219	231	217	216	216	238
High-efficiency										
Median	755	753	747	746	754	786	796	781	769	764
IQR	267	261	253	281	265	244	253	270	262	276
DHE18										
Low-efficiency										
Median	506	506	507	505	505	506	506	507	508	509
IQR	98	97	98	117	121	122	125	135	132	138
High-efficiency										
Median	626	625	624	623	654	689	714	698	682	674
IQR	171	173	170	169	177	188	190	224	201	195
DHE19										
Low-efficiency										
Median	613	615	640	660	797	1,008	1,160	1,232	1,261	1,379
IQR	576	583	568	565	599	553	689	771	890	956
High-efficiency										
Median	679	707	735	747	792	823	838	876	867	912
IQR	477	473	469	475	511	524	513	480	441	498
DHE22										
Low-efficiency										
Median	667	663	652	653	666	765	823	861	885	904
IQR	409	402	401	424	433	417	392	382	370	378
High-efficiency										
Median	651	652	648	650	663	670	687	689	693	695
IQR	298	299	299	302	302	284	285	286	284	297
DHEFF										
Low-efficiency										
Median	780	780	779	781	805	870	912	943	966	991
IQR	194	201	194	193	202	202	232	270	285	316

Concentrations are in parts per million (ppm).

5.2. Carbon Monoxide (CO)

Indoor carbon monoxide (CO) levels are influenced by outdoor CO levels. It is also commonly linked to the spillage of exhaust gases from vented appliances that use CO-producing fuels.[30] Household background CO levels can fluctuate due to factors such as tobacco smoke and the types of heating and cooking fuels used (NY DOH, 2010). While the US Environmental Protection Agency (EPA) does not establish specific numeric standards for CO in residential indoor air, its US National Ambient Air Quality Standards for outdoor air are 9 ppm over an 8-hour average, and 35 ppm over a 1-hour average (EPA 2025a, 2025b).

Table 7 presents medians and interquartile ranges of CO concentrations in the direct-heated space for low- and high-efficiency units across all sites. The values are reported in 5-minute intervals, from 15 minutes before the start of heating cycles through the first 30 minutes of the cycles. The data show that CO concentrations increased during heater operation at some sites. In DHE05, DHE14, DHE15, DHE19, DHE22, and DHEFF, CO concentrations increased during operation of the low-efficiency units and, to a lesser extent—or even not at all (DHE19)—during operation of the high-efficiency units. In a few cases (DHE11, DHE16, and DHE18), no change in CO concentration was observed after the low-efficiency units started, but CO concentrations did increase during the first 5-15 minutes of high-efficiency unit operation and then declined.

Most of the sites listed above, where CO concentrations increased during operation of the low-efficiency unit, also experienced increased CO_2 concentrations. The increases in CO concentrations reinforce the suggestion that exhaust gases were spilled into the living space during low-efficiency unit operation and that, during high-efficiency unit operation, the combustion fans mitigated the spillages.[31] Some other potential sources of indoor air CO can also be considered. For example, the increase in CO concentration during heater operation could be explained by higher occupancy of the directly heated space combined with smoking. In addition, at sites where the direct-heated space is open or adjacent to the kitchen, it could be explained by households turning the heater on while they are cooking (and then eating). To understand why these same activities would lead to a lower, or even no, increase in concentration during high-efficiency operation compared with low-efficiency operation, one should factor in the contribution of the convection fans in spreading and dissipating the CO throughout the space, which likely reduces the concentration at the sensor.

However, despite the potential contribution of heaters to increasing CO concentrations in direct-heated spaces, the median CO concentration in these spaces during DHE heating operations was typically below 2 ppm, with most sites recording levels under 1 ppm. The only exception is DHE19, where the median CO value increased from 0.8 ppm to 5.2 ppm during the first 30 minutes of operation of the low-efficiency unit. It should be noted, however, that due to the limitations of the CO measurement modules and potential changes in occupant behavior, these

[30] For CO level to rise in the home from appliance operation, two things must happen: The appliance burner needs to produce substantial amounts of CO, which is uncommon, and that CO needs to enter the living space instead of being vented.

[31] Note, however, that our initial spillage test did not show any spillage from the low-efficiency units.

results should not be considered conclusive.

In addition, although no critical increases in CO concentrations were observed during regular DHE operation, two high-efficiency units unexpectedly released elevated CO levels into the living space at two sites due to heater malfunctions. In both events, the monitoring system detected CO levels above safe levels, and the households were promptly contacted to shut down the units. The manufacturer subsequently replaced the faulty units. In both cases, the malfunctions were attributed to manufacturing issues, which the manufacturer reported it would correct immediately. Appendix D compares CO concentration distributions during operation and non-operation periods for both low- and high-efficiency units.

Table 7: CO Concentration in the Direct-Heated Space

Site	**Time relative to heating cycle start** (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE01										
Low-efficiency										
Median	0.3	0.3	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.2
IQR	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
High-efficiency										
Median	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4
IQR	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
DHE05										
Low-efficiency										
Median	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.8	0.9	1.0
IQR	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8
High-efficiency										
Median	0.4	0.4	0.4	0.4	0.5	0.7	0.7	0.7	0.8	0.8
IQR	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6
DHE10[32]										
Low-efficiency										
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IQR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
High-efficiency										
Median	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IQR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DHE11										
Low-efficiency										
Median	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.0
IQR	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1
High-efficiency										
Median	0.7	0.7	0.7	0.7	0.8	0.9	0.9	0.8	0.8	0.8
IQR	0.5	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6

[32] Measurements were below the sensor's limit of detection (LOD).

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE14										
Low-efficiency										
Median	0.7	0.7	0.8	0.8	1.2	1.4	1.7	1.7	1.7	1.8
IQR	0.1	0.1	0.1	0.1	0.1	0.01	0.1	0.03	0.03	0.1
High-efficiency										
Median	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.4
IQR	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
DHE15										
Low-efficiency										
Median	1.5	1.5	1.5	1.5	1.6	1.8	2.0	2.0	2.0	2.0
IQR	0.9	0.9	0.9	0.9	1.0	0.9	0.8	0.8	0.8	0.8
High-efficiency										
Median	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.7	0.6	0.6
IQR	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
DHE16										
Low-efficiency										
Median	0.7	0.7	0.7	0.6	0.7	0.8	0.7	0.7	0.6	0.6
IQR	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
High-efficiency										
Median	0.5	0.6	0.6	0.5	0.7	0.9	0.9	0.8	0.7	0.7
IQR	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
DHE18										
Low-efficiency										
Median	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
IQR	0.7	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7
High-efficiency										
Median	1.2	1.2	1.2	1.2	1.3	1.5	1.5	1.4	1.3	1.3
IQR	0.9	0.9	0.9	0.9	0.9	1.1	1.0	1.0	0.9	0.9
DHE19										
Low-efficiency										
Median	0.6	0.6	0.6	0.8	2.0	3.6	4.3	5.3	5.2	5.2
IQR	2.4	2.5	2.5	2.5	4.8	8.4	9.9	10.2	10.4	11.0
High-efficiency										
Median	0.6	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9	0.9
IQR	0.8	0.9	0.9	1.0	1.1	1.3	1.3	1.5	1.7	1.8
DHE22										
Low-efficiency										
Median	1.1	1.1	1.2	1.1	1.3	1.4	1.5	1.5	1.5	1.5
IQR	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.7
High-efficiency										
Median	0.9	0.9	0.9	0.9	1.0	1.1	1.1	1.1	1.0	1.0
IQR	0.9	0.9	0.9	1.0	0.9	0.8	0.9	0.9	0.9	0.9

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHEFF										
Low-efficiency										
Median	0.4	0.4	0.4	0.4	0.5	0.6	0.8	0.9	0.9	1.0
IQR	1.1	1.0	1.0	1.0	1.1	1.2	1.7	1.8	1.8	1.8

Concentrations are in parts per million (ppm).

5.3. Particulate Matter 2.5 ($PM_{2.5}$)

Indoor levels of fine particulate matter are often higher than outdoor concentrations. The EPA (2025b) sets a maximum long-term average $PM_{2.5}$ exposure of 9 µg/m^3 and a maximum 24-hour average of 35 µg/m^3 for ambient air quality.

Table 8 presents medians and interquartile ranges of $PM_{2.5}$ concentrations in the direct-heated space for low- and high-efficiency units across all sites. The values are reported in 5-minute intervals, from 15 minutes before the start of heating cycles through the first 30 minutes of the cycles. Except for DHE18 and DHE22, concentrations were typically higher during the period when the low-efficiency units were monitored than during the period when the high-efficiency units were monitored, with the highest median value observed across all periods being 13.3 µg/m^3.[33] However, the concentration levels before and during heater operation do not indicate that the heaters could have had any effect on $PM_{2.5}$ concentration.[34] Appendix E compares $PM_{2.5}$ concentration distributions during operation and non-operation periods for both low- and high-efficiency units.

Table 8: $PM_{2.5}$ Concentration in the Direct-Heated Space

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE01										
Low-efficiency										
Median	2.3	2.3	2.3	2.2	2.3	2.3	2.2	2.1	2.1	2.2
IQR	2.8	2.8	2.9	2.9	2.8	2.7	2.8	2.8	2.8	2.8
High-efficiency										
Median	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5
IQR	2.0	2.1	2.0	1.9	2.0	2.0	2.0	1.9	2.0	1.9

[33] Note that, while PM standards are in gravimetric mass, our measurements are based on PM optical sensors. To convert our results to their equivalent gravimetric mass, multiply them by a correction factor of 0.6 to 0.65.
[34] Examples of potential sources of indoor $PM_{2.5}$ are: combustion activities (cooking, smoking, candles), infiltration of outdoor pollution, occupant activities that resuspend dust (vacuuming, cleaning, walking), consumer products (spray cleaning products, hairsprays, aerosol products), and biological sources (pet dander, mold spores, dust mites).

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE05										
Low-efficiency										
Median	6.1	6.3	6.5	6.2	6.4	5.9	5.4	5.1	5.2	4.9
IQR	7.9	8.8	9.5	8.7	8.8	8.3	8.1	8.1	8.9	9.7
High-efficiency										
Median	2.9	2.9	2.9	2.9	2.7	2.4	2.2	2.1	2.2	2.1
IQR	4.8	5.0	4.9	5.2	4.4	4.0	3.7	3.7	3.6	3.6
DHE10										
Low-efficiency										
Median	5.1	4.7	4.9	4.5	4.5	4.0	4.2	4.2	4.1	4.1
IQR	6.4	6.5	6.9	6.7	6.4	5.5	5.8	6.0	5.5	5.4
High-efficiency										
Median	3.9	3.7	4.0	3.9	3.6	3.3	3.3	3.6	3.5	3.8
IQR	6.7	7.4	7.0	6.8	5.0	4.3	5.0	5.3	5.3	5.4
DHE11										
Low-efficiency										
Median	2.1	2.2	2.2	2.2	2.0	2.0	2.1	2.0	1.9	2.0
IQR	1.7	1.8	1.6	1.6	1.8	1.7	1.7	1.6	1.6	1.6
High-efficiency										
Median	1.4	1.3	1.5	1.4	1.3	1.4	1.4	1.3	1.3	1.5
IQR	1.4	1.7	1.5	1.6	1.5	1.7	1.7	1.7	1.5	1.4
DHE14										
Low-efficiency										
Median	12.2	10.6	11.2	9.1	9.4	9.3	8.5	8.5	7.4	7.6
IQR	9.4	7.1	7.9	6.3	5.9	6.8	5.4	5.1	4.7	4.9
High-efficiency										
Median	3.3	3.5	3.2	3.7	3.3	3.0	3.0	4.3	3.6	3.3
IQR	1.0	1.8	1.9	2.4	2.2	2.9	2.9	3.8	5.5	6.4
DHE15										
Low-efficiency										
Median	4.9	4.5	5.0	4.4	4.5	4.6	4.5	4.5	4.8	4.2
IQR	3.4	2.7	3.2	2.8	2.8	2.1	3.0	3.1	3.1	3.1
High-efficiency										
Median	2.4	2.5	2.4	2.3	2.3	2.2	2.1	2.2	2.1	2.1
IQR	2.4	2.2	2.6	2.4	2.5	2.6	2.5	2.4	2.4	2.5
DHE16										
Low-efficiency										
Median	6.6	6.3	6.6	6.6	6.3	5.9	6.3	6.8	6.9	6.8
IQR	8.1	8.1	8.4	8.5	8.6	7.7	8.2	8.1	8.2	8.9
High-efficiency										
Median	3.1	3.1	3.1	3.1	3.1	2.7	2.7	2.7	2.8	3.0
IQR	5.8	6.1	6.2	6.6	6.2	5.3	4.9	6.4	5.8	6.4

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE18										
Low-efficiency										
Median	6.7	6.4	6.5	6.6	6.2	6.1	6.0	6.1	5.7	5.8
IQR	7.3	7.4	7.6	6.8	7.2	7.0	6.9	7.0	6.9	7.2
High-efficiency										
Median	12.4	12.4	11.9	11.5	13.3	12.2	11.1	11.9	11.5	10.4
IQR	27.1	22.7	27.6	22.2	37.4	32.1	28.2	24.9	23.8	21.4
DHE19										
Low-efficiency										
Median	2.2	2.2	2.2	2.4	2.7	2.6	2.5	2.3	2.4	2.6
IQR	4.0	3.8	4.1	4.6	4.4	4.3	4.3	4.3	4.2	4.3
High-efficiency										
Median	1.3	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.4	1.5
IQR	2.6	2.9	3.0	3.4	3.0	3.4	3.2	3.7	3.7	3.7
DHE22										
Low-efficiency										
Median	1.6	1.7	1.4	2.4	1.8	2.0	1.9	2.1	2.9	2.5
IQR	1.7	1.7	1.1	1.9	1.0	1.2	1.1	1.6	11.7	35.8
High-efficiency										
Median	6.5	5.8	6.7	7.7	7.9	6.9	7.3	7.4	7.8	8.2
IQR	22.7	23.1	26.0	26.2	32.7	33.0	31.9	34.3	39.5	36.5
DHEFF										
Low-efficiency										
Median	1.8	1.8	1.8	1.7	1.8	1.7	1.7	1.7	1.7	1.7
IQR	2.0	2.0	2.1	2.1	1.9	1.9	1.8	1.7	1.7	1.6

Concentrations are in micrograms per cubic meter (µg/m^3).

5.4. Particulate Matter 10 (PM_{10})

Although the EPA does not set specific numeric standards for PM_{10} in residential indoor air, its outdoor National Ambient Air Quality Standard (NAAQS) sets a 24-hour average below 150 µg/m^3 as a safe level for indoor PM_{10} (EPA, 2025b).

Table 9 presents medians and interquartile ranges of PM_{10} concentrations in the direct-heated space for low- and high-efficiency units across all sites. The values are reported in 5-minute intervals, from 15 minutes before the start of heating cycles through the first 30 minutes of the cycles. Similar to $PM_{2.5}$ concentrations,[35] PM_{10} concentrations were typically higher when the low-efficiency units were monitored than when the high-efficiency units were monitored, except for DHE18 and DHE22. The highest median value observed across all periods was 13.3 µg/m^3.[33] However, the concentration levels before and during heater operation do not indicate

[35] A significant fraction of PM_{10} is made up of $PM_{2.5}$.

that the heaters had any effect on PM_{10} concentration. Appendix F compares PM_{10} concentration distributions during operation and non-operation periods for both low- and high-efficiency units.

Table 9: PM_{10} Concentration in the Direct-Heated Space

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE01										
Low-efficiency										
Median	2.3	2.4	2.3	2.3	2.5	2.3	2.3	2.3	2.3	2.2
IQR	2.9	2.8	2.9	2.8	2.8	2.7	2.7	2.8	2.8	2.7
High-efficiency										
Median	1.6	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
IQR	2.0	2.2	2.1	2.0	2.1	2.0	2.1	2.1	2.1	2.0
DHE05										
Low-efficiency										
Median	6.2	6.3	6.6	6.2	6.5	5.9	5.4	5.1	5.2	4.9
IQR	7.9	8.7	9.5	8.8	8.7	8.4	8.5	8.4	8.9	9.9
High-efficiency										
Median	3.3	3.1	3.1	3.2	2.9	2.6	2.5	2.3	2.4	2.3
IQR	4.9	5.1	5.1	5.3	4.5	4.2	4.1	3.7	3.6	3.6
DHE10										
Low-efficiency										
Median	5.1	4.7	4.9	4.5	4.5	4.0	4.2	4.2	4.1	4.1
IQR	6.3	6.5	6.8	6.7	6.3	5.4	5.6	6.0	5.4	5.3
High-efficiency										
Median	4.0	3.8	4.2	4.0	3.7	3.5	3.4	3.7	3.5	3.8
IQR	6.6	7.3	6.9	6.6	4.9	4.3	4.9	5.3	5.3	5.3
DHE11										
Low-efficiency										
Median	2.5	2.4	2.3	2.4	2.3	2.4	2.3	2.2	2.2	2.2
IQR	1.8	2.1	1.9	2.0	2.0	2.1	1.8	1.8	1.7	1.6
High-efficiency										
Median	1.8	1.5	1.7	1.5	1.5	1.4	1.6	1.6	1.8	1.7
IQR	2.0	2.1	1.8	2.2	1.9	1.9	2.0	2.1	2.0	1.8
DHE14										
Low-efficiency										
Median	13.1	11.5	12.0	9.7	9.9	9.8	9.1	9.0	7.8	8.2
IQR	10.2	7.9	8.8	6.9	6.3	7.3	5.8	5.5	5.0	5.3
High-efficiency										
Median	3.7	3.5	3.2	4.8	4.1	4.2	3.6	4.5	4.5	4.0
IQR	1.5	2.7	2.6	2.6	2.6	3.1	3.5	4.3	6.4	6.7

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE15										
Low-efficiency										
Median	4.9	4.5	5.0	4.5	5.1	5.0	4.5	4.5	4.8	4.4
IQR	3.1	2.2	2.7	2.2	2.2	1.6	2.4	2.4	2.4	2.4
High-efficiency										
Median	2.4	2.5	2.4	2.3	2.3	2.2	2.1	2.3	2.1	2.1
IQR	2.5	2.2	2.6	2.4	2.5	2.6	2.4	2.4	2.4	2.5
DHE16										
Low-efficiency										
Median	6.6	6.4	6.6	6.6	6.3	5.9	6.3	6.8	6.9	6.8
IQR	8.1	8.1	8.5	8.5	8.4	7.6	8.0	8.1	8.2	8.9
High-efficiency										
Median	3.3	3.2	3.2	3.2	3.1	2.7	2.8	3.1	2.9	3.0
IQR	5.7	6.0	6.2	6.4	6.1	5.1	4.8	6.3	5.6	6.4
DHE18										
Low-efficiency										
Median	6.7	6.4	6.5	6.6	6.2	6.1	6.2	6.3	5.8	5.8
IQR	7.3	7.4	7.6	7.1	7.2	7.0	6.9	7.0	6.9	7.2
High-efficiency										
Median	12.7	12.4	12.5	12.3	13.3	12.5	11.3	12.1	11.7	10.7
IQR	27.8	23.1	27.2	22.5	38.6	32.5	28.9	24.9	23.5	21.5
DHE19										
Low-efficiency										
Median	2.2	2.3	2.2	2.5	2.9	2.7	2.6	2.5	2.6	2.7
IQR	4.0	4.1	4.6	4.8	4.7	4.4	4.3	4.3	4.2	4.4
High-efficiency										
Median	1.4	1.6	1.6	1.6	1.6	1.7	1.7	1.6	1.5	1.6
IQR	2.7	3.1	3.1	3.4	3.0	3.4	3.2	3.6	3.8	3.6
DHE22										
Low-efficiency										
Median	1.7	1.8	1.6	2.5	2.3	2.2	2.0	2.7	2.9	2.6
IQR	1.9	2.0	1.3	2.0	1.1	1.7	1.3	1.5	11.7	35.9
High-efficiency										
Median	6.6	6.0	6.9	7.7	7.9	7.1	7.4	7.5	7.9	8.2
IQR	23.0	23.2	26.2	27.0	33.5	33.6	32.5	35.1	40.4	36.9
DHEFF										
Low-efficiency										
Median	2.0	1.9	1.9	1.9	1.9	1.9	1.9	1.9	2.0	2.0
IQR	2.0	2.0	2.1	2.0	1.9	1.8	1.7	1.8	1.8	1.7

Concentrations are in micrograms per cubic meter (µg/m^3).

5.5. Total Volatile Organic Compounds (TVOC)

TVOC encompasses a range of chemicals, and indoor concentrations of many VOC typically exceed outdoor levels (EPA, 2025c). Currently, there are no standardized guidelines for indoor TVOC levels.

Table 10 presents medians and interquartile ranges of TVOC concentrations in the direct-heated space for low- and high-efficiency units across all sites. The values are reported in 5-minute intervals, from 15 minutes before the start of heating cycles through the first 30 minutes of the cycles. The data show that TVOC concentrations increased during heater operation in some sites. In DHE05 and DHEFF, TVOC concentrations increased during the operation of the low-efficiency unit and, to a lesser extent (DHE05), during the operation of the high-efficiency unit. In DHE19, TVOC increased slightly during operation of the low-efficiency unit and more markedly during operation of the high-efficiency unit. In DHE14 and DHE15, TVOC concentration increased only during operation of the high-efficiency unit, although it mostly remained below that concentration during operation of the low-efficiency unit.

During combustion, VOCs are emitted either when the fuel does not burn completely or when VOCs present in the raw natural gas pass through the burner unburned. If combustion pollutants spill into the living space, the TVOC indoor concentration may increase due to unburned fuel VOCs. Assuming that the new units vent exhaust gases more effectively, one would expect consistently smaller increases in TVOC concentration during operation of the high-efficiency units than during operation of the low-efficiency units.[36] However, the field data do not support this expected general pattern. In addition, the differences in concentration levels between low- and high-efficiency operations are not statistically significant, nor are they when comparing concentrations during the heater-on and heater-off periods. We therefore rule out the possibility that the heaters affected TVOC concentrations in the direct-heated space and attribute those concentrations to household activities, sometimes conducted there during heater operation.

TVOC concentrations varied across sites. In most sites, concentrations were below 500 ppb during heater operation. However, when the low-efficiency unit was operating in DHE05, DHE19, and DHFF, TVOC concentrations ranged from 500 ppb to 1500 ppb; during the high-efficiency unit's operation, TVOC concentrations in DHE15 and DHE19 ranged from 1500 ppb to 3000 ppb. Note that not all VOCs have health implications, and little is known about the health effects of the levels of organic compounds typically found in homes (EPA, 2025c). Nevertheless, the findings suggest that improved ventilation strategies and source control measures may be necessary to reduce indoor TVOC exposures on some sites with elevated TVOC levels, particularly DHE15. Appendix G compares TVOC concentration distributions during operation and non-operation periods for both low- and high-efficiency units.

[36] Similar to what was suggested regarding CO_2 (Section 5.1) and CO (Section 5.2) concentrations.

Table 10: TVOC Concentration in the Direct-Heated Space

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE01										
Low-efficiency										
Median	389	390	393	391	397	402	407	408	408	406
IQR	433	429	422	410	408	426	443	445	436	429
High-efficiency										
Median	658	690	670	672	725	724	715	710	715	708
IQR	863	865	857	823	876	871	818	814	785	774
DHE05										
Low-efficiency										
Median	520	513	537	697	982	1,197	1,300	1,301	1,356	1,494
IQR	1,568	1,472	1,569	1,825	2,530	4,376	4,218	4,930	4,513	4,606
High-efficiency										
Median	347	333	366	379	456	498	506	522	551	559
IQR	575	573	538	559	690	793	880	867	955	941
DHE10										
Low-efficiency										
Median	365	364	360	359	389	429	440	439	435	459
IQR	327	312	319	326	369	384	349	343	338	357
High-efficiency										
Median	897	887	903	919	998	1,035	1,034	1,039	1,041	1,087
IQR	750	720	752	728	788	860	861	941	954	891
DHE11										
Low-efficiency										
Median	456	441	451	454	487	490	492	508	509	496
IQR	545	556	567	574	537	562	547	530	569	566
High-efficiency										
Median	548	504	523	568	556	548	573	635	660	776
IQR	949	930	906	1,051	950	1,143	1,105	1,117	1,122	1,221
DHE14										
Low-efficiency										
Median	1,036	1,048	1,189	1,234	784	1,235	1,219	1,101	968	1,010
IQR	205	15	67	119	39	272	319	182	124	186
High-efficiency										
Median	215	206	215	206	278	327	334	354	385	435
IQR	67	105	52	87	55	110	86	71	114	109
DHE15										
Low-efficiency										
Median	2,480	2,500	2,134	2,320	2,281	2,354	2,750	2,418	2,449	2,328
IQR	2,980	2,996	3,118	3,181	3,509	3,442	3,811	2,509	1,739	2,126
High-efficiency										
Median	1,725	1,713	1,736	1,690	2,141	2,104	2,226	2,498	2,552	2,821
IQR	2,581	2,542	2,583	2,150	2,777	2,515	2,770	2,949	3,306	3,460

Site	Time relative to heating cycle start (*min*)									
	-15	*-10*	*-5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*
DHE16										
Low-efficiency										
Median	407	388	377	351	376	404	396	367	355	350
IQR	542	529	525	531	532	547	521	458	481	467
High-efficiency										
Median	1,262	1,240	1,202	1,191	1,202	1,227	1,213	1,154	1,127	1,172
IQR	1,632	1,586	1,640	1,631	1,687	1,632	1,678	1,710	1,691	1,732
DHE18										
Low-efficiency										
Median	182	181	181	182	183	182	182	182	182	181
IQR	110	111	105	109	113	123	119	124	118	119
High-efficiency										
Median	565	565	559	571	600	596	616	615	587	561
IQR	513	519	498	493	524	548	530	415	456	503
DHE19										
Low-efficiency										
Median	648	640	598	725	927	950	942	982	902	997
IQR	1,551	1,722	1,757	1,810	2,211	2,046	2,002	2,183	2,079	2,015
High-efficiency										
Median	1,028	1,078	1,172	1,220	1,711	1,796	1,899	2,074	2,224	2,264
IQR	2,440	2,534	2,524	2,520	3,296	3,835	3,556	3,634	3,718	3,913
DHE22										
Low-efficiency										
Median	153	151	150	161	149	136	134	162	141	171
IQR	331	326	316	320	332	344	347	364	368	433
High-efficiency										
Median	367	369	349	350	411	391	390	406	415	414
IQR	652	660	650	672	692	669	677	680	704	702
DHEFF										
Low-efficiency										
Median	558	547	543	561	536	616	693	742	803	827
IQR	1,098	1,091	1,045	1,057	1,049	1,119	1,254	1,208	1,279	1,315

Concentrations are in parts per billion (ppb).

6. Users' Feedback and Improvements to DHE Models

6.1. Households' Perspectives on High-Efficiency DHE Models

Nine households completed the survey we conducted at the end of the high-efficiency model monitoring, regarding their satisfaction with the new heater and how it compares with the old one.[37] When comparing the new equipment with the previous units, all participants indicated that the new DHE units were at least somewhat better at heating the entire space more quickly, delivering warmer air, and achieving a more even heat distribution. Six respondents reported improved overall comfort, and seven reported enhanced temperature controls. Feedback on indoor air quality was more varied: four households reported improvement, two worsening, and three felt air quality was only "somewhat" improved. Regarding overall satisfaction, five respondents described themselves as "Very Satisfied," one as "Satisfied," two as "Dissatisfied," and one as "Very Dissatisfied." The most common complaint about the new equipment was noise: five respondents said the new unit was not quieter than their previous equipment. The three households not satisfied with their new unit cited noise as a key reason, with one even describing the unit as "overstimulating." One household reported frequent breakdowns, and another cited mechanical failure, thermostat issues, maintenance errors, and unresolved service issues as reasons for their dissatisfaction with the new unit.

Regarding potential changes in their natural gas bills due to the higher-efficiency unit, two respondents reported slightly lower bills, two reported slightly higher bills, and the remaining five were unsure whether there were any changes. Reasons for uncertainty included the possibility of small changes, insufficient attention to billing details, or difficulty isolating the impact due to multiple gas appliances in the home. When asked if they would choose this model if purchasing a replacement heater themselves, responses were evenly split: three answered "Yes," three answered "Maybe," and three answered "No." Similarly, five respondents said they would recommend the model to friends or family, while four would not. Those unwilling to repurchase or recommend the model primarily cited noise and reliability concerns, with two participants also mentioning the bulkier size as a drawback. As for positive features, respondents appreciated improved thermostat controls, faster space heating, better heat distribution from the fan, and reduced odors during operation. In terms of willingness to pay a premium, five participants would spend $500 more than a standard replacement, four would pay $1,000 more, and three would pay $1,500 more for this model. No respondent was willing to pay more than a $2,000 premium for the advanced DHE unit. In open-ended feedback, one satisfied participant noted they would have switched even without incentives.

Overall, responses were mixed. While nearly all participants acknowledged improvements in heating speed and distribution, satisfaction with the units was more divided. Three of nine respondents said they would not repurchase the model, and four would not recommend it to

[37] Note that these views reflect only the experiences of the households that participated in this fieldwork regarding high-efficiency *versus* low-efficiency DHE. They do not represent the opinions of all DHE users in California or across the United States.

others, citing noise and reliability concerns as the primary reasons. These findings suggest that while high-efficiency DHE units offer meaningful performance benefits, addressing noise and reliability issues, particularly in the models where they were most observed, may be important for broader acceptance.

6.2. Improvements to High-Efficiency DHE and Their Installation

Our evaluation of low- and high-efficiency DHE units in the field identified several key areas for further investigation by industry and researchers: unit efficiency, heat output modulation, safety mechanisms, venting design, noise, and installation practices.

First, unit efficiency remains a significant challenge. The high-efficiency models we tested are rated as 80% to 82% AFUE, which was the best available at the time. To surpass this level, condensing-type furnaces would be necessary, but they introduce complications with condensate management. While direct-vent models can technically accommodate this, B-vent upright wall furnaces—often installed in central interior walls—pose greater difficulties. Previously, direct-vent condensing DHE models with AFUE ratings near 90% were available, but these have been discontinued. Future research should focus on developing practical solutions for condensate management in B-vent installations and carefully weighing the costs and benefits of condensing DHE units for California homes.

Another important consideration is the modulation of heat output in high-efficiency models. While multiple heat settings can improve thermal comfort—as shown by both field data and user feedback—the optimal number of output levels and their impact on combustion efficiency remain poorly understood. Some units offer up to seven different output settings, but in practice, the heater typically operates in only one to three levels. If the burner design is not optimized for the full range or the most common settings, efficiency may drop. Therefore, systematic research is needed to evaluate the trade-offs of heat modulation in DHE units under controlled conditions, especially at different heating levels.

Safety is another critical consideration. DHE models should, in general, incorporate safeguards to prevent combustion products, especially carbon monoxide, from leaking into living spaces. This is particularly relevant to high-efficiency DHE models, which typically include a combustion fan. The fan is intended to supply the air needed for combustion and force the exhaustion of combustion gases through the vent, mitigating the effects of backdrafting. However, failure of key components related to that system, such as a thermocouple sensor, can lead to improper fan operation, resulting in insufficient combustion air, incomplete combustion, and the release of carbon monoxide indoors. Adding a sensor to monitor the combustion fan could detect malfunctions and automatically cut off the unit's gas supply. Similarly, installing a carbon monoxide sensor near the air intake of upright, non-direct-vent wall furnaces could serve as a safety mechanism, shutting down the unit in the event of a backdraft or other failure. Note that, while mechanisms that mitigate safety-critical events should ideally be incorporated into any DHE model, it may make more sense to implement such innovations in newer, high-end, high-efficiency models currently under development or undergoing design improvements.

Alternatively, the venting system in non-direct-vent upright wall furnaces could be redesigned. Adopting the concentric venting system used in direct-vent models would reduce the risk of backdrafting and of combustion products leaking into the living space. Since high-efficiency models already feature a combustion fan, the fan could both expel exhaust gases and draw in fresh combustion air from outside the home.

Further improvements to the evaluated upright high-efficiency wall furnace model include repositioning the combustion fan intake higher in the unit to prevent debris accumulation from dust, carpet fibers, or pet hair. The thermostat interface was also found to be complicated and unintuitive, making adjustments difficult for participants. Additionally, fan noise was one of the most significant concerns raised by participants and the primary driver of dissatisfaction among users of that model who expressed negative overall assessments. Participants noted that the fans were noisy, making the unit unsuitable for living rooms or bedrooms, which can be a barrier to model acceptance. Potential approaches to reduce noise include using quieter fan motors or optimizing fan speed control during low-output operation. Further, noise levels in decibels should be disclosed on specification sheets so that installers and homeowners can make informed decisions prior to purchase and installation.

From an installation standpoint, a major safety concern involves converting units to operate with either natural gas or propane. This process requires installers to adjust the gas regulator pressure and replace the fuel supply orifice accordingly. Although conversion kits and instructions are available, not all conversions are performed correctly, posing significant safety risks. For instance, during our field evaluation, one site (DHE01) featured an older DHE unit connected to a natural gas line, even though it was labeled for propane. The homeowner believed the installer had made the necessary adjustments, but laboratory inspection revealed the unit was still configured for propane (Blum et al., 2024b). Discussions with manufacturers confirmed that incorrect or incomplete conversions are common, as many installers lack proper knowledge or training. Improper fuel conversion can compromise both efficiency and safety. Future research should explore new model designs that enable seamless dual-fuel installations and address this critical safety issue.

7. Conclusions

This field evaluation examined energy consumption, improvements in indoor temperature and air quality, and user satisfaction associated with DHE in 11 California households. It should be noted that the 11 households constitute a small sample, and therefore, the findings are not statistically representative of the broader fleet of DHE units in California and the United States. By monitoring low-efficiency baseline units, subsequently replacing 10 of the 11 low-efficiency units with high-efficiency models, and monitoring their performance over additional heating seasons, the study provided empirical insights into the real-world performance of advanced DHE technologies. Additionally, the evaluation identified critical field safety hazards, including CO leakage from manufacturing defects that would likely go undetected in laboratory testing alone, underscoring the value of real-world field evaluations for identifying risks to occupants' health and safety.

Field data indicate that switching to high-efficiency DHE units reduced natural gas consumption per heating degree day by 20% to 40% across five monitored sites. On another site, replacing a wall furnace installed in the early 1950s reduced natural gas consumption per heating degree day by 80%. However, at four sites, natural gas use increased by 10% to slightly more than double. This was likely due to a rebound effect. In these households, improved temperature controls and enhanced thermal comfort may have led to more frequent or longer heater use. While the rebound effect may have reduced energy savings, the increased use of the heater also led to greater consumer welfare, as reflected in the thermal comfort gained at the expense of the additional energy consumption. Although high-efficiency models require electricity for combustion and circulation fans, this additional energy use was negligible, ranging from 0.1% to 0.9% of the total natural gas consumption. Overall, high-efficiency models improved thermal comfort by providing faster warming, higher peak temperatures, and more uniform heat distribution within the heated spaces.

The data also show, in some cases, an increase in indoor concentrations of CO_2 and CO in the directly heated space during heater operation, with larger average increases, ranging from 130 ppm to 600 ppm of CO_2 and from 0.2 ppm to 3.3 ppm of CO, during operation of low-efficiency units compared with high-efficiency units. These increases have likely been driven by the spillage of combustion pollutants during low-efficiency unit operation, which may have been prevented by the high-efficiency unit's combustion fans. In addition, household behavior and emission sources may have also played a role. As for the observed changes in $PM_{2.5}$, PM_{10}, and TVOC concentrations during the operation of some heaters, we find no evidence in the data that the changes were driven by the heaters and therefore believe that household sources other than the heaters were responsible. Although some pollutant concentrations increased during heater operation, we did not detect any critical exposure levels under standard operating conditions. However, we did identify critical safety concerns: specifically, two high-efficiency units leaked elevated levels of CO into living spaces due to manufacturing defects, requiring immediate shutdown and replacement. This finding highlights the importance of rigorous quality control in DHE manufacturing processes and safety certification.

Participant feedback confirmed the measured thermal improvements: the nine participants who completed the survey reported that the new units heated spaces more quickly and evenly. Users also valued the enhanced thermostat controls and reduced operating odors. However, overall satisfaction was partially diminished by equipment noise, with several households reporting that the new circulation and combustion fans were too loud for living rooms or bedrooms. Opinions regarding the reliability and perceived cost savings of the new units were mixed.

Based on the knowledge gained in this study, we recommend that industry and future research address key areas to maximize efficiency, safety, and market adoption of high-efficiency DHE. These key areas emerged directly from field observations, safety incidents, and participant feedback gathered over three heating seasons, and are intended to inform both product development and future research.

The first area concerns DHE efficiency and modulation design. Improving DHE efficiency beyond 80-82% AFUE requires condensing models, which in turn necessitate practical solutions for condensate management, especially in non-direct-vent upright wall furnaces. Additionally, the trade-offs associated with multi-level heat modulation should be systematically evaluated to ensure high combustion efficiency across all heat settings, for example, by adjusting the amount of combustion air at each setting.

The second key area involves the safety of these units. High-efficiency models should include integrated sensors to monitor combustion fan operation and carbon monoxide levels, and should automatically shut off the gas supply in the event of a malfunction or backdraft. Implementing concentric venting systems, as used in direct-vent models, for upright wall furnaces could also prevent combustion products from entering indoor spaces.

The third area pertains to installation and usability improvements. Improper conversions between natural gas and propane can pose significant safety risks; manufacturers should develop designs and provide instructions and training to enable safe, seamless dual-fuel installations. Usability enhancements should include quieter fans, elevated combustion fan intakes to prevent debris from the floor from entering the unit, and simplified thermostat interfaces for consumers.

While this study provides important insights, several limitations should be considered when interpreting the results. First, although we were able to enroll a diverse set of households throughout various locations and with a range of baseline unit models and vintages, the evaluation was limited to a small sample of 11 households. Second, the study spanned three heating seasons, during which weather conditions changed, and household occupancy or heating behavior may have varied. Even though we normalized energy use to heating degree days for the days the heaters were used, we did not account for human factors that influence heater usage. Third, while we attribute reductions in CO_2 and CO concentrations to high-efficiency units' performance, these gases' concentrations remain sensitive to human metabolism and intermittent household activities such as cooking, heavy smoking, or appliance

use. These and other factors may have affected the measurements of indoor air quality variables. Future studies could mitigate the effects of these factors by monitoring occupancy, recording participants' activities, or using more controlled experimental designs that isolate the effects of DHE operation from other household activities. Nevertheless, to the best of our knowledge, our findings are relevant for supporting future analyses of the benefits of high-efficiency DHE.

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Appendix A: DHE Units Evaluated in the Field

List of Figures

The figures in this Appendix show the units we evaluated at each site. All pictures of the new, high-efficiency units were taken immediately after installation, before the walls were patched.

Low-Efficiency DHE
Montgomery Ward & Co SBI 9084

High-Efficiency DHE
Rinnai EX11CTN

Figure A-1. Units Evaluated in the DHE01 Site

The existing unit, around 50 years old, had an oversized capacity relative to the space's heating needs. The replacement unit capacity was determined based on Manual J load calculations performed for this house.

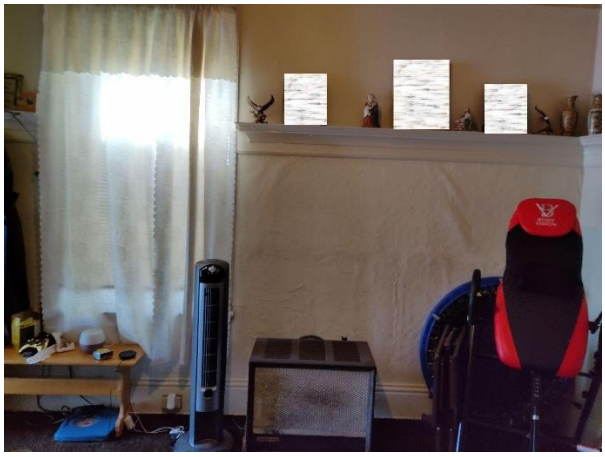
Low-Efficiency DHE
Williams 2001622A

High-Efficiency DHE
Rinnai EX38CTWN

Figure A-2. Units Evaluated in the DHE05 Site

The DHE was relocated to an exterior wall so the team could replace the former low-efficiency room heater, which used a B-vent installed on an old fireplace, with a high-efficiency, direct-vent model.

Low-Efficiency DHE
Perfection Shwank VC235TN-W-1



High-Efficiency DHE
Rinnai EX38CTN

Figure A-3. Units Evaluated in the DHE10 Site

The old, low-efficiency room heater was replaced with a new direct-vent, high-efficiency model.

Low-Efficiency DHE
Williams 3509822 + fan (add-on)

High-Efficiency DHE
Williams AC2030TN

Figure A-4. Units Evaluated in the DHE11 Site

The household had an external accessory fan that helped distribute the warm air from the gravity wall furnace. The new high-efficiency model has the same footprint as the previous unit and includes an electronically controlled variable-speed circulation fan that delivers better warm-air distribution.

Low-Efficiency DHE
Honeywell 867.7336

High-Efficiency DHE
Williams AC3040TN

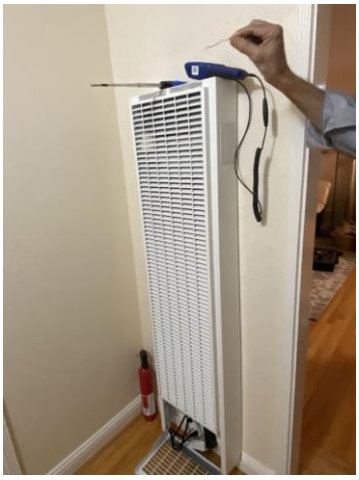


Figure A-5. Units Evaluated in the DHE14 Site

The new high-efficiency model replaced a double-sided vintage model estimated at about 70 years old.

Low-Efficiency DHE
Williams C50D|C60D

High-Efficiency DHE
Williams AC2030TN
Motorized Rear Outlet Register (#6919)

Figure A-6. Units Evaluated in the DHE15 Site

The original low-efficiency, gravity double-sided wall furnace was oversized for the home's heating needs. It was replaced with a high-efficiency, single-sided wall furnace with a coupled accessory fan that blows warm air to the second space through the wall, mimicking the old unit's service but with lower energy requirements.

Low-Efficiency DHE
Williams 2509622

High-Efficiency DHE
Williams AC2030TN

Figure A-7. Units Evaluated in the DHE16 Site

The former low-efficiency gravity wall furnace was replaced with a high-efficiency model with the same footprint and a circulation fan that provides better warm-air distribution.

Low-Efficiency DHE
Unknown make/model

High-Efficiency DHE
Williams AC2030TN

Figure A-8. Units Evaluated in the DHE18 Site

The former vintage wall furnace (circa 70 years old) had no legible nameplate. It was replaced with a high-efficiency wall furnace that includes a circulation fan, which provides a better distribution of warm air. The replacement unit's capacity was determined based on Manual J load calculations performed for this house.

Low-Efficiency DHE
Williams 14DV-3-NAT

High-Efficiency DHE
Rinnai EX22CTN

Figure A-9. Units Evaluated in the DHE19 Site

The former direct-vent DHE was upgraded to a high-efficiency model.

Low-Efficiency DHE
Williams 30DV-5

High-Efficiency DHE
Rinnai EX38CTN

Figure A-10. Units Evaluated in the DHE22 Site

The former direct-vent DHE was upgraded to a high-efficiency, direct-vent model.

Low-Efficiency DHE
Custom-Aire G-35

Figure A-11. Unit Evaluated in the DHEFF Site

This is a vintage floor furnace unit (circa 70 years old). Because no high-efficiency floor furnace models are on the market, this heater was not replaced.

Appendix B: Temperature and Relative Humidity in Various Spaces of the Homes

List of Figures

The figures in this Appendix present, for the low- and high-efficiency units on each site, temperature and temperature change at the four heights of the stratification tree, as well as temperature, temperature change, relative humidity, and change in relative humidity in various spaces of the home.

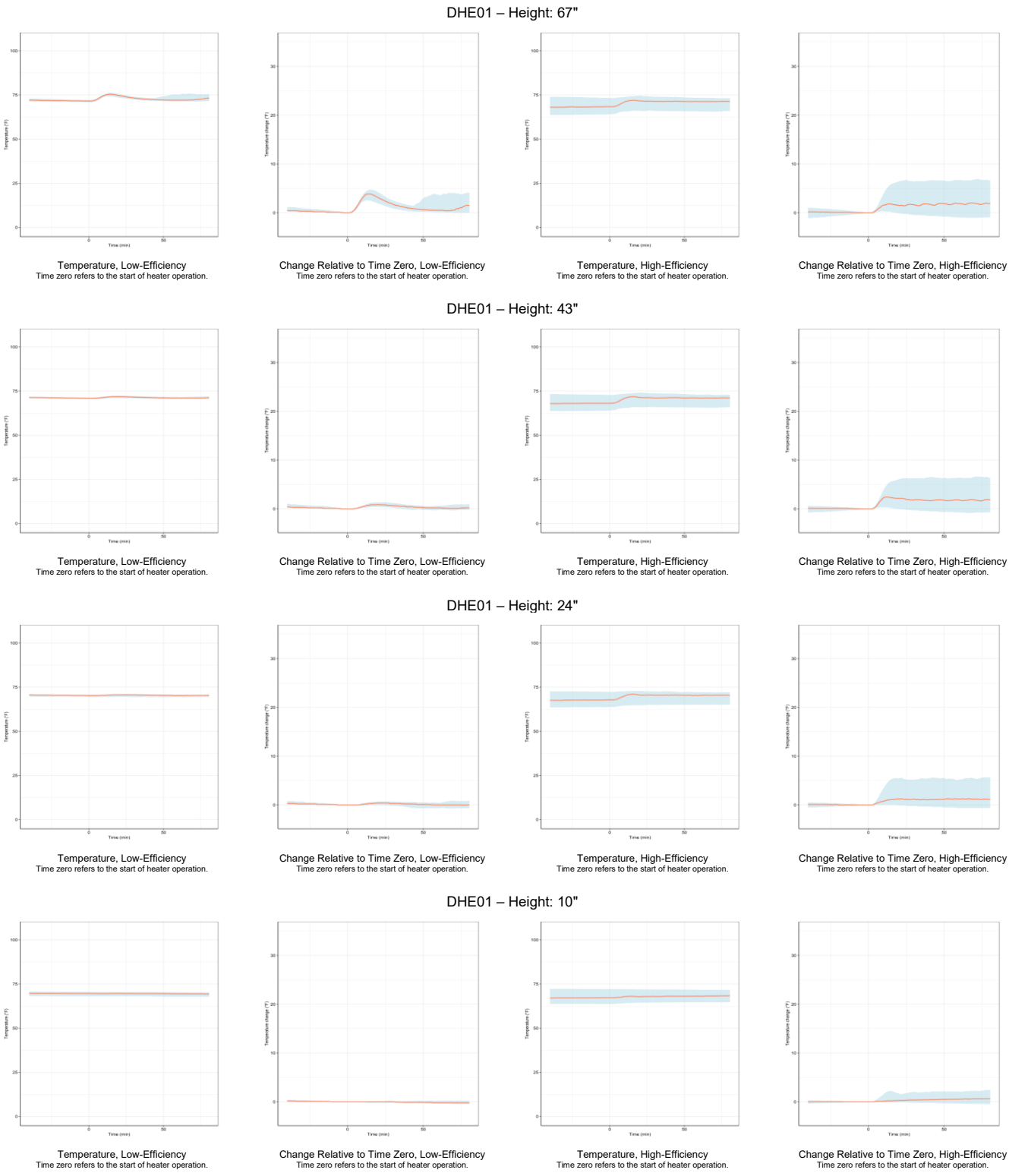


Figure B-1. DHE01 Temperature at various heights of the stratification tree during operation periods

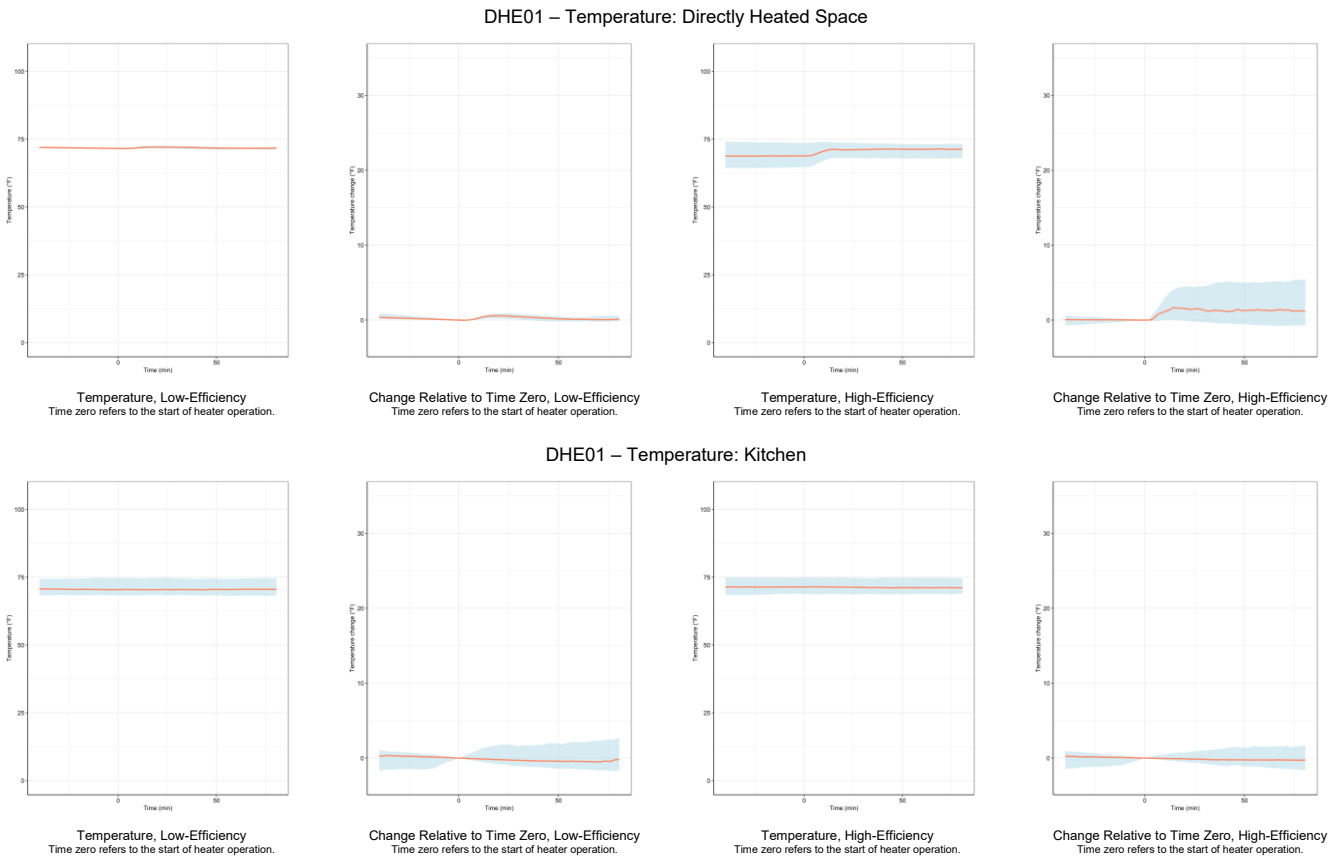


Figure B-2. DHE01 Temperature at different spaces in the home during operation periods

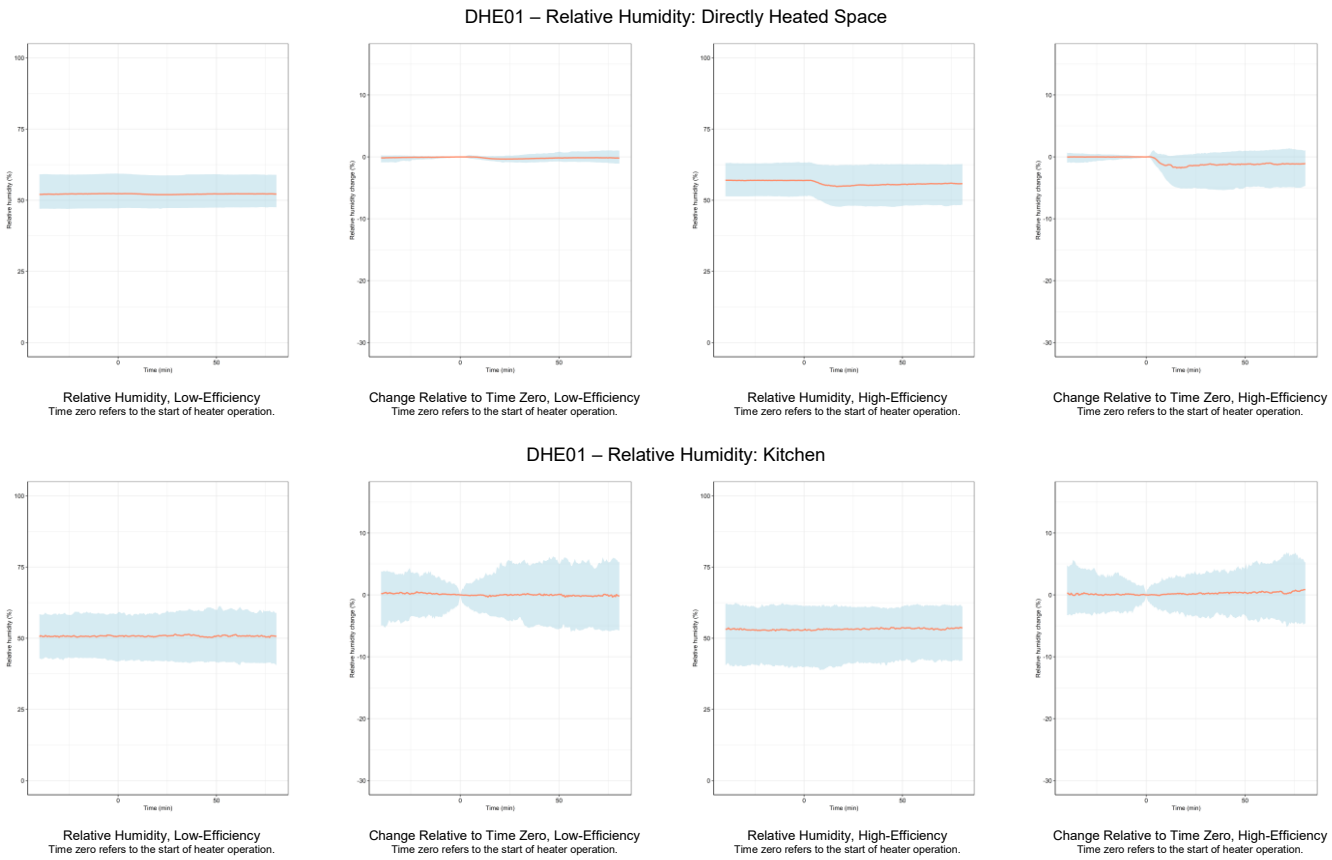


Figure B-3. DHE01 Relative Humidity in different spaces in the home during operation periods

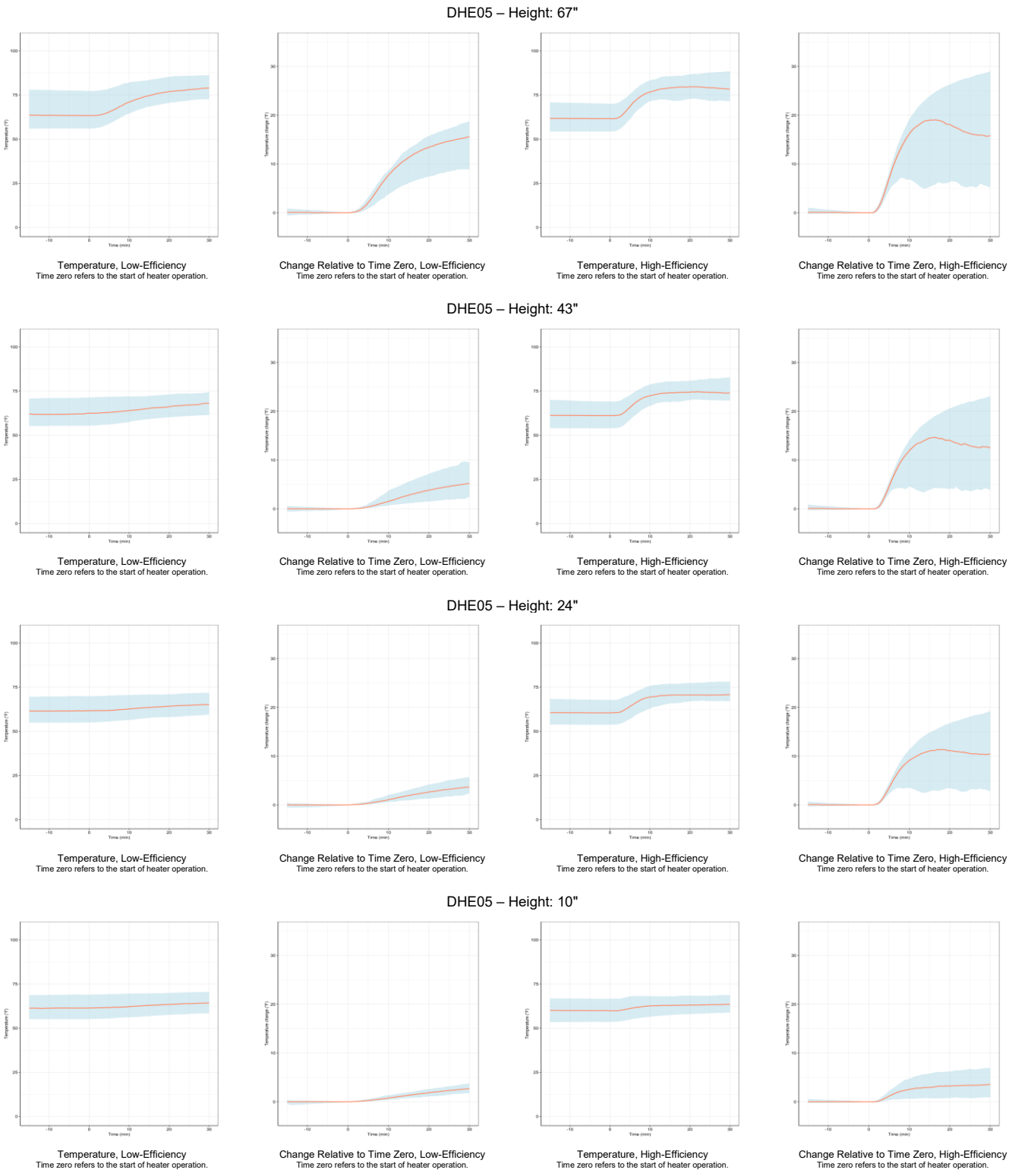
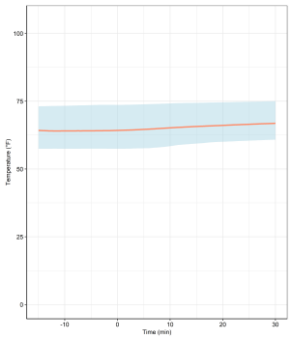
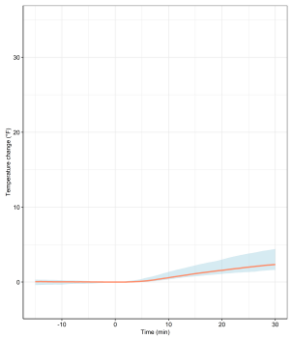


Figure B-4. DHE05 Temperature at various heights of the stratification tree during operation periods

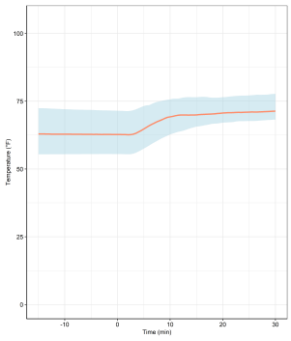
DHE05 – Temperature: Directly Heated Space



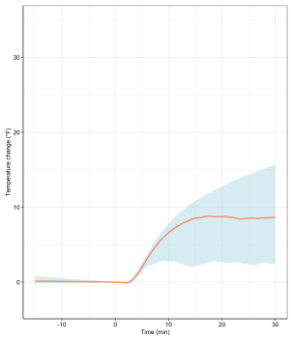
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

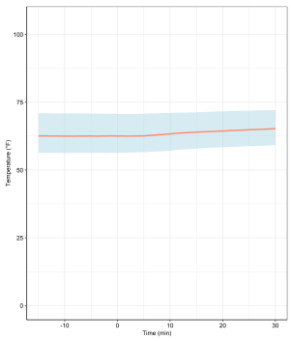


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

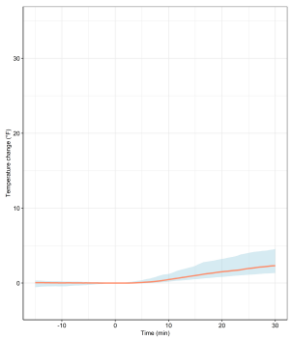


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

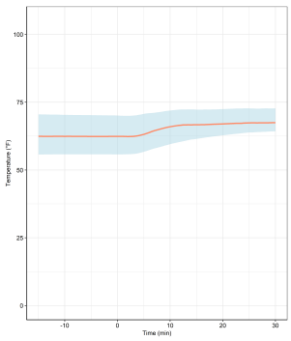
DHE05 – Temperature: Kitchen



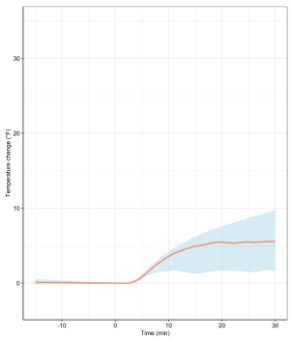
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

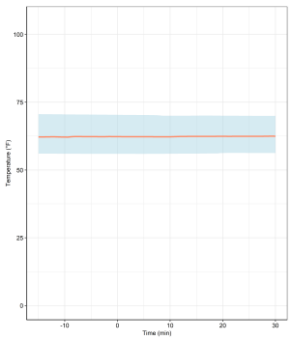


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

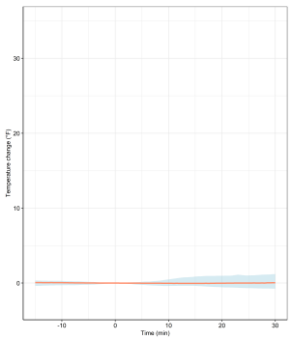


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

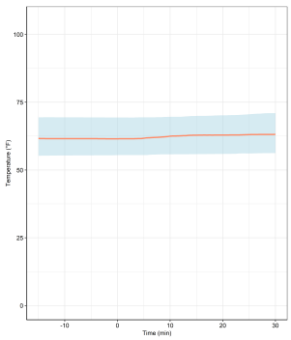
DHE05 – Temperature: Bedroom



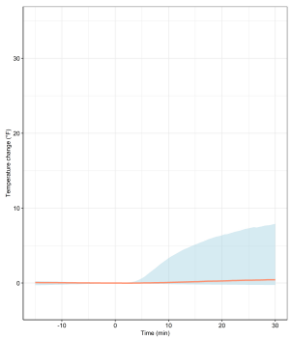
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



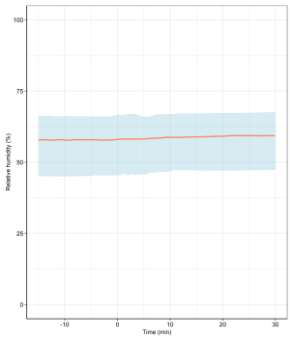
Temperature, High-Efficiency
Time zero refers to the start of heater operation.



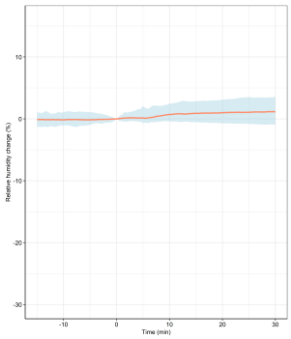
Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-5. DHE05 Temperature at different spaces in the home during operation periods

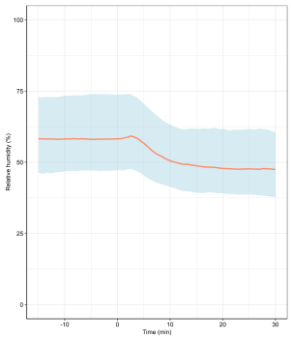
DHE05 – Relative Humidity: Directly Heated Space



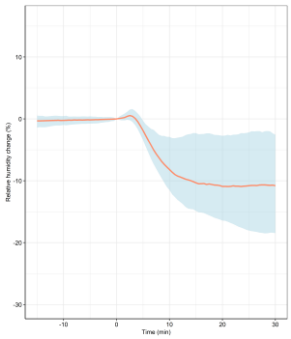
Relative Humidity, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

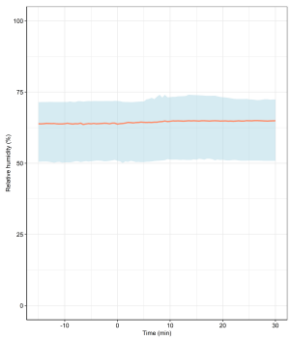


Relative Humidity, High-Efficiency
Time zero refers to the start of heater operation.

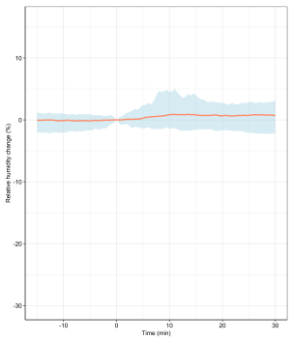


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

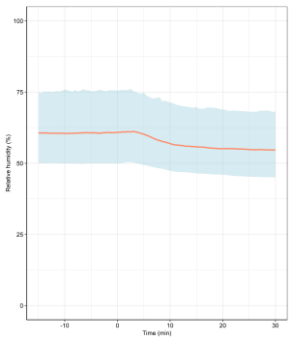
DHE05 – Relative Humidity: Kitchen



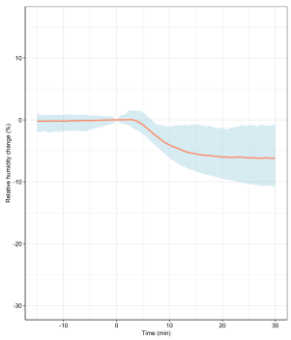
Relative Humidity, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

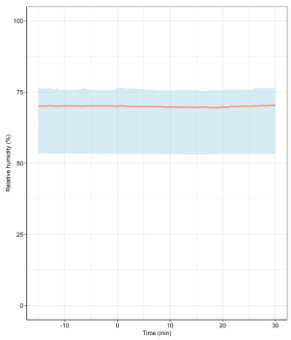


Relative Humidity, High-Efficiency
Time zero refers to the start of heater operation.

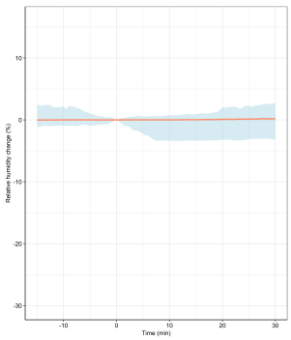


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

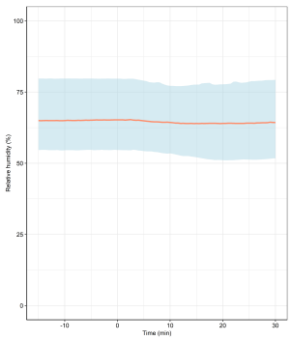
DHE05 – Relative Humidity: Bedroom



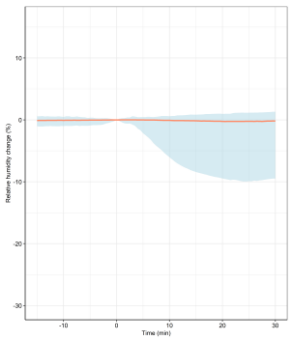
Relative Humidity, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



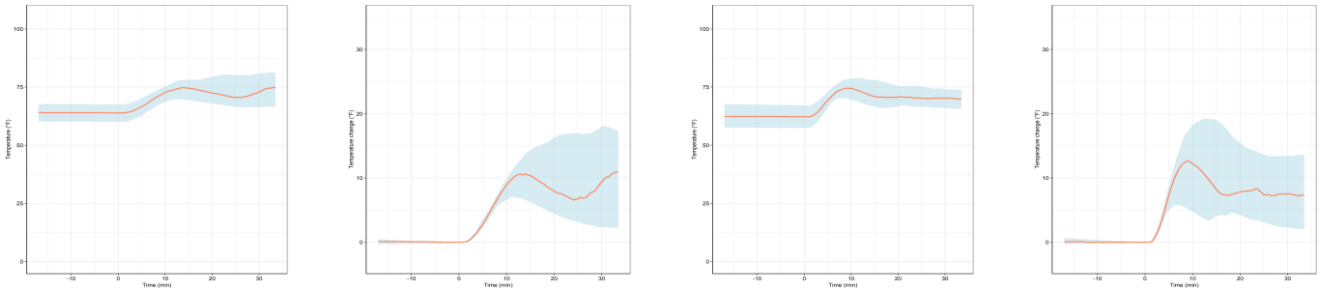
Relative Humidity, High-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-6. DHE05 Relative Humidity in different spaces in the home during operation periods

DHE10 – Height: 67"



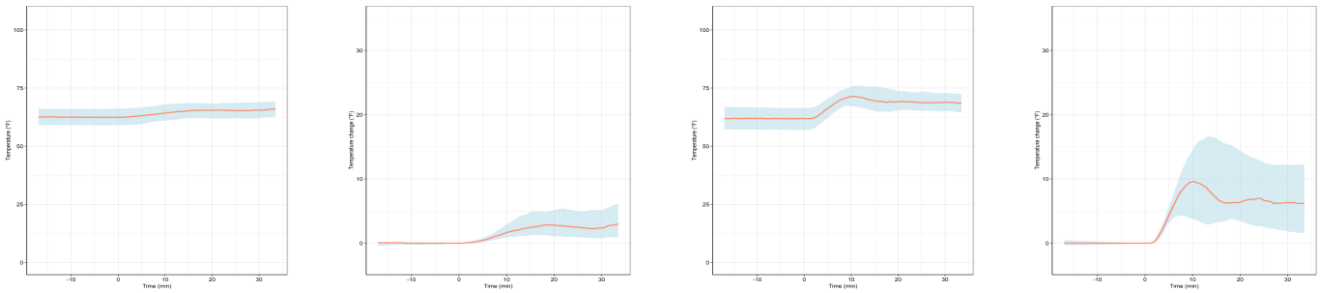
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE10 – Height: 43"



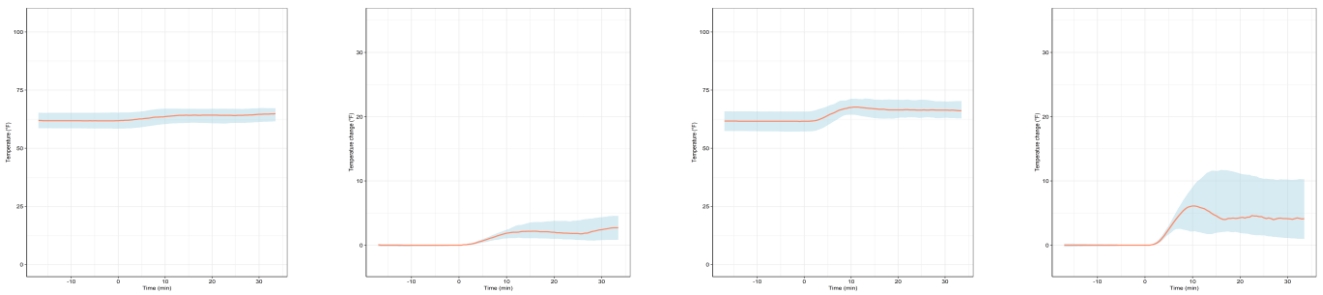
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE10 – Height: 24"



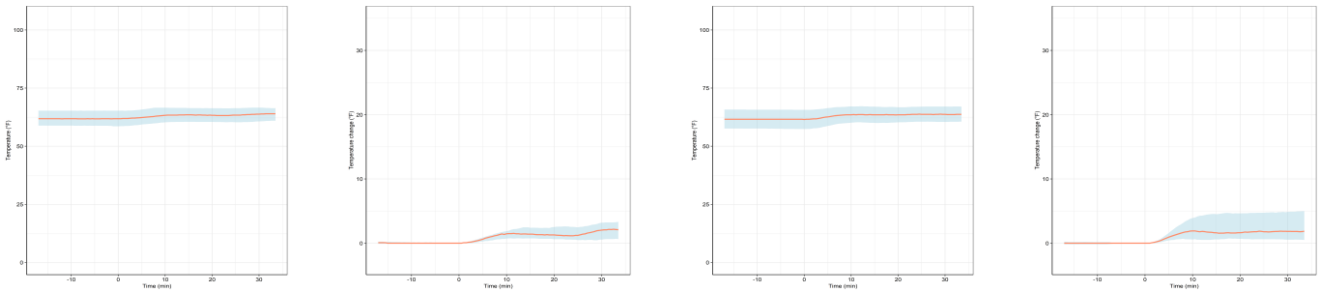
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE10 – Height: 10"



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

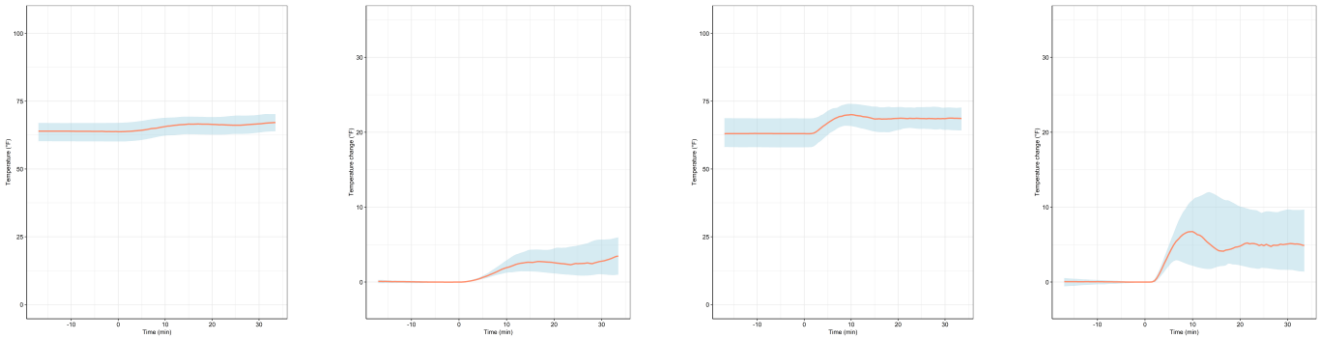
Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-7. DHE10 Temperature at various heights of the stratification tree during operation periods

DHE10 – Temperature: Directly Heated Space



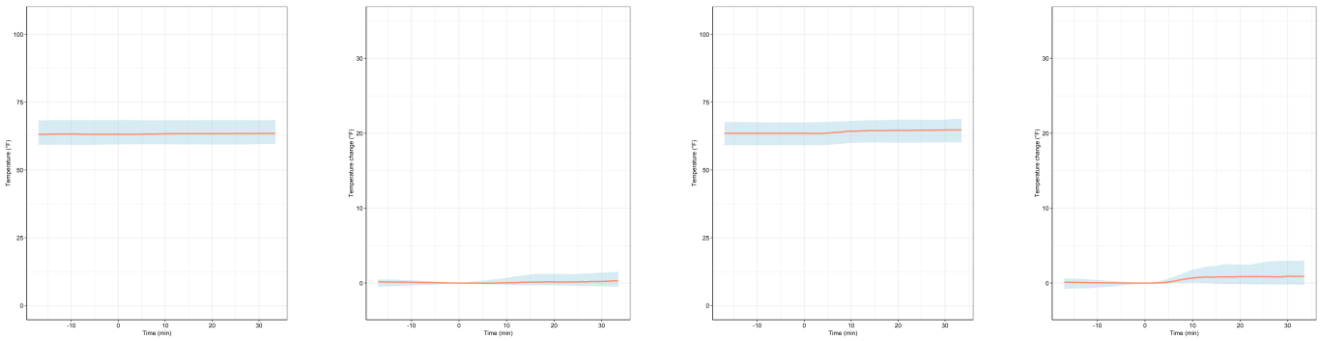
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE10 – Temperature: Kitchen



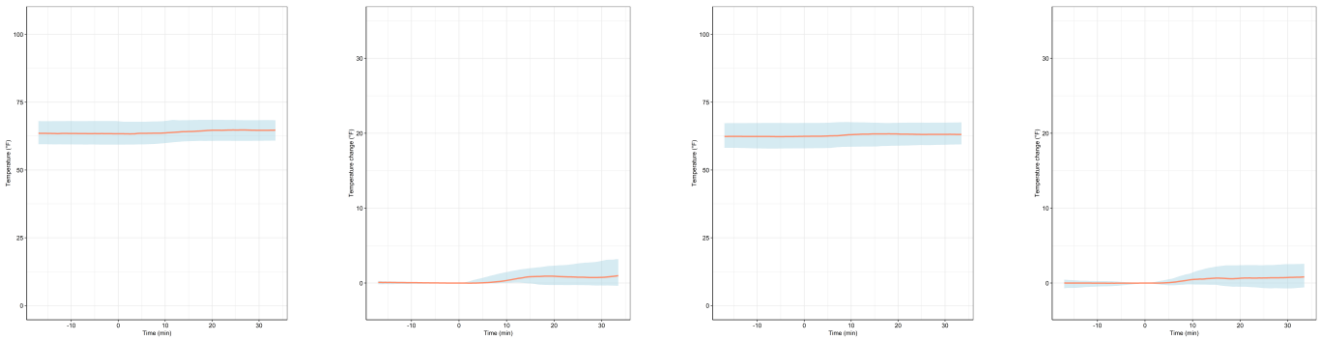
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE10 – Temperature: Bedroom



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-8. DHE10 Temperature at different spaces in the home during operation periods

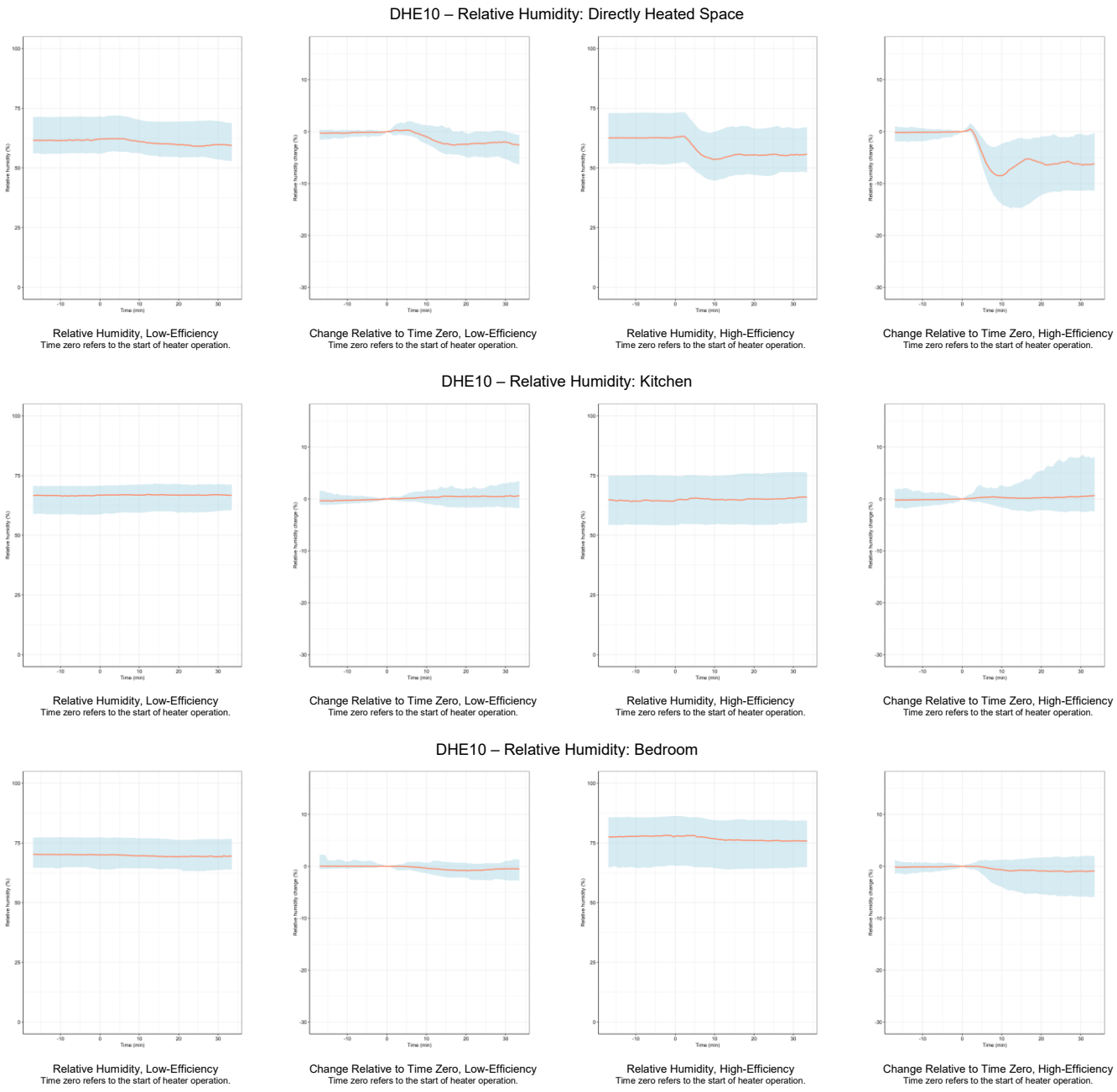
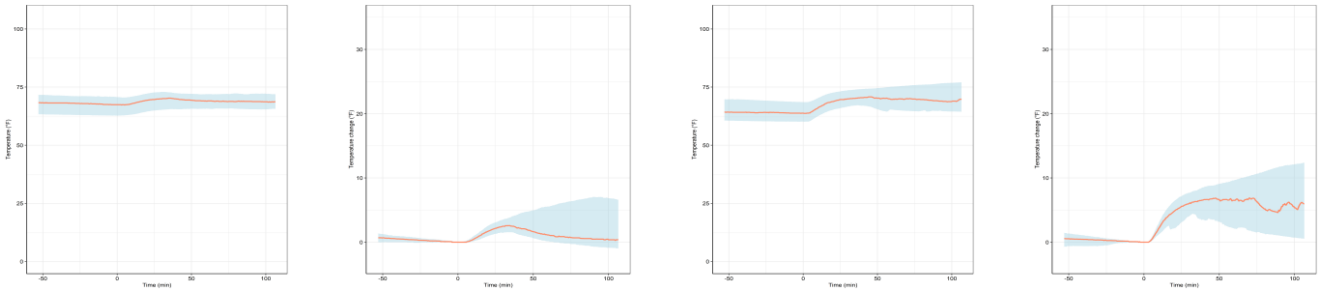


Figure B-9. DHE10 Relative Humidity in different spaces in the home during operation periods

DHE11 – Height: 67"



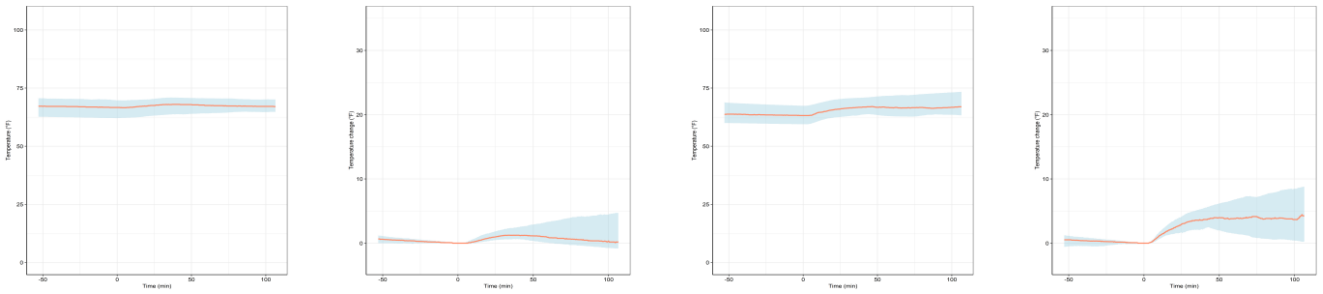
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE11 – Height: 43"



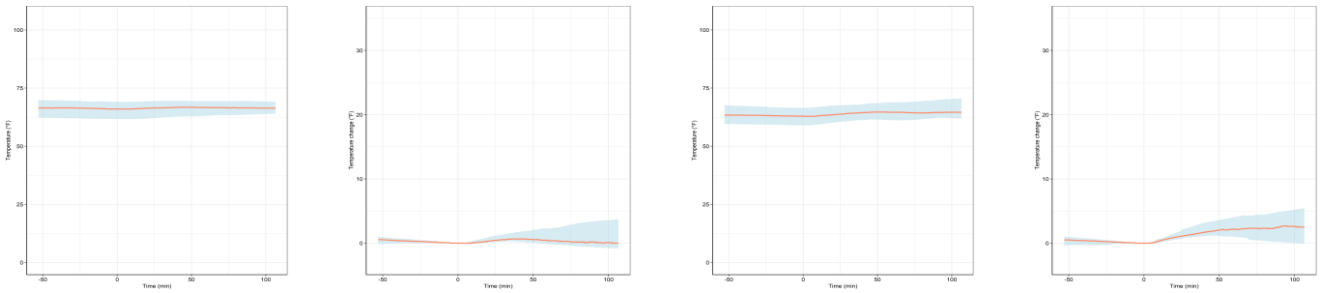
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE11 – Height: 24"



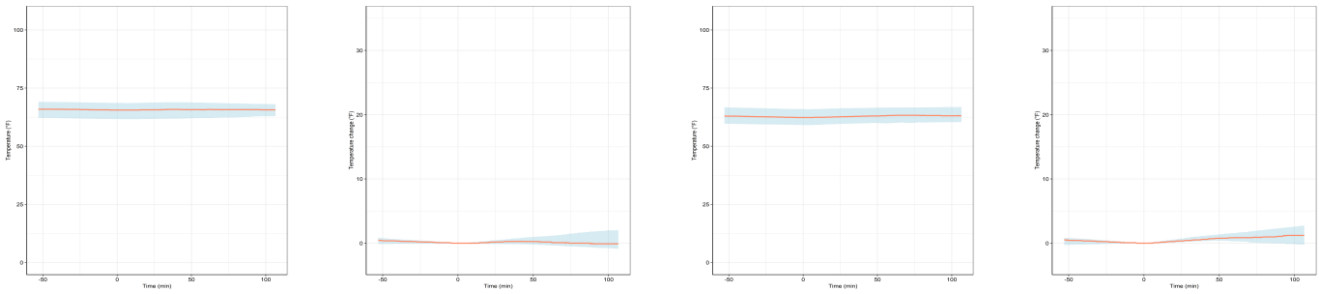
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE11 – Height: 10"



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

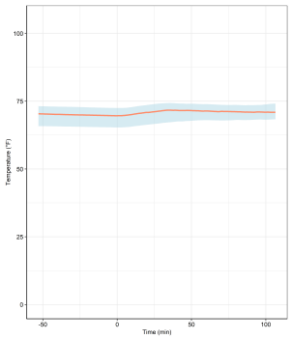
Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

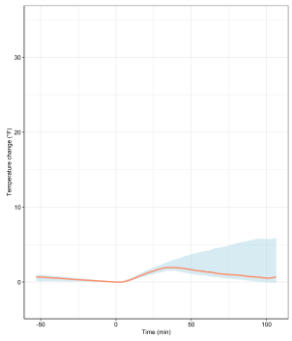
Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-10. DHE11 Temperature at various heights of the stratification tree during operation periods

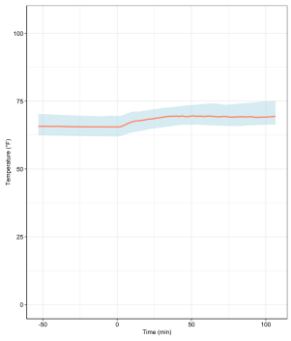
DHE11 – Temperature: Directly Heated Space



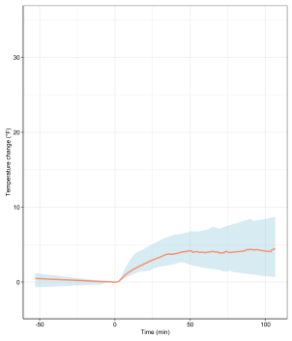
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

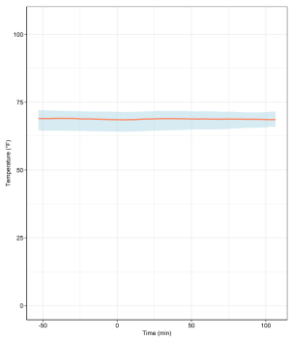


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

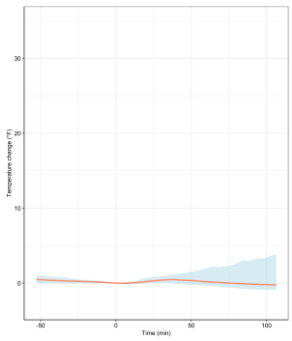


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

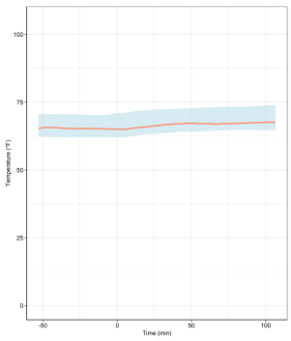
DHE11 – Temperature: Kitchen



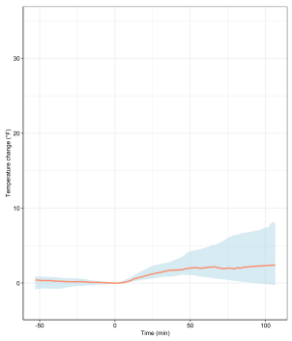
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

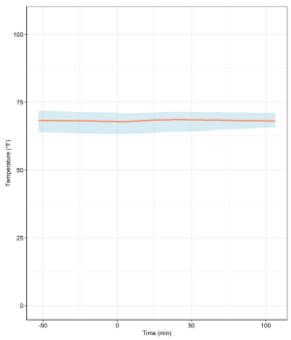


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

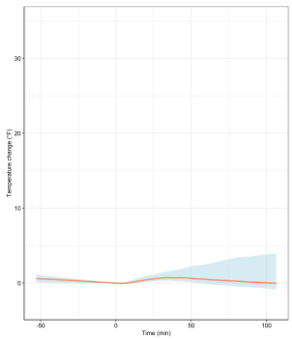


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

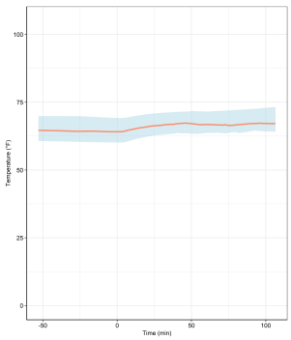
DHE11 – Temperature: Living Room



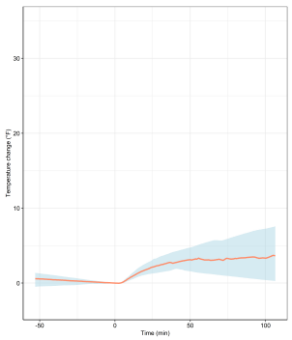
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



Temperature, High-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-11. DHE11 Temperature at different spaces in the home during operation periods

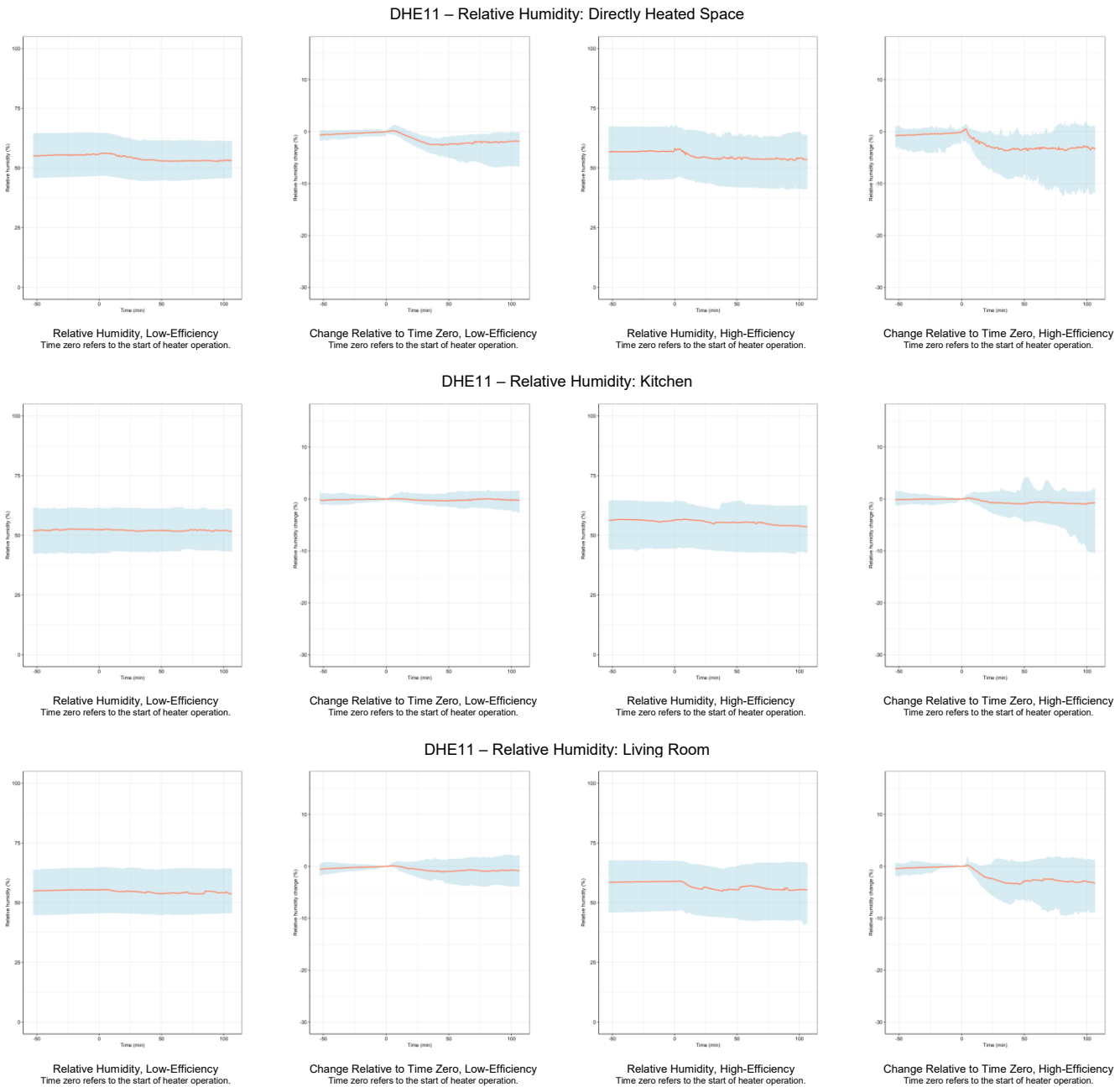
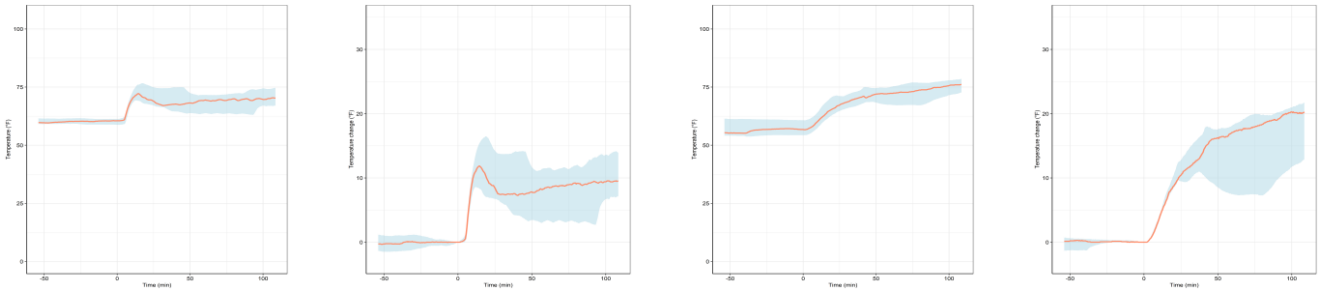


Figure B-12. DHE11 Relative Humidity in different spaces in the home during operation periods

DHE14 – Height: 67"



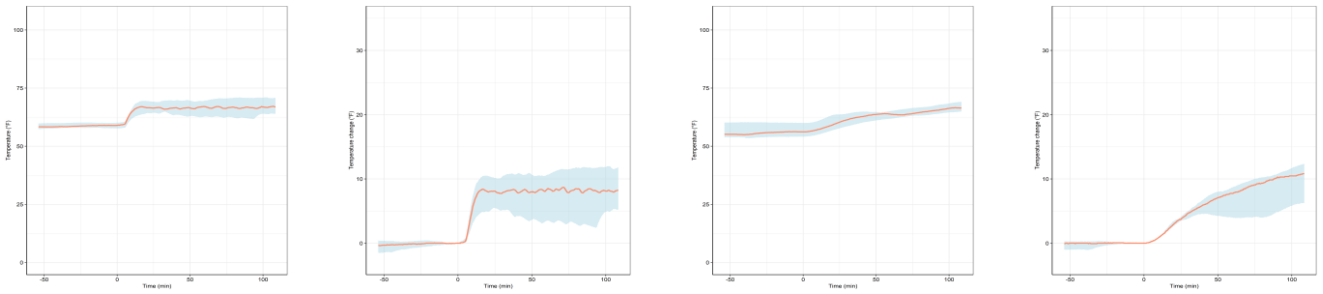
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE14 – Height: 43"



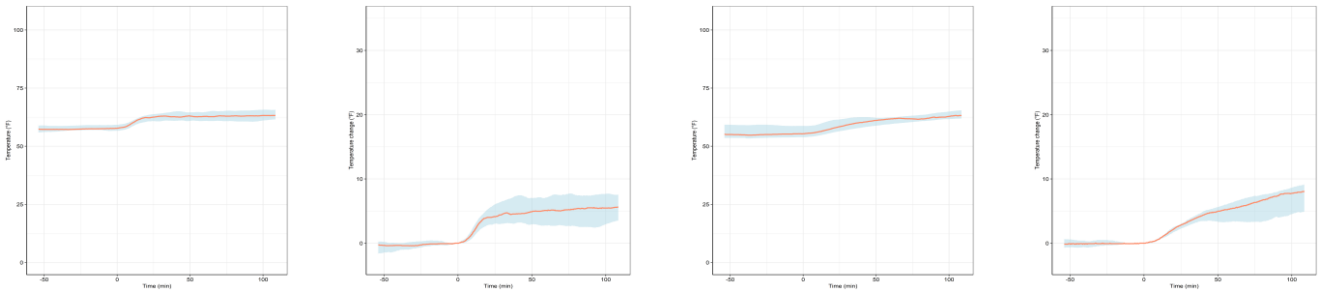
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE14 – Height: 24"



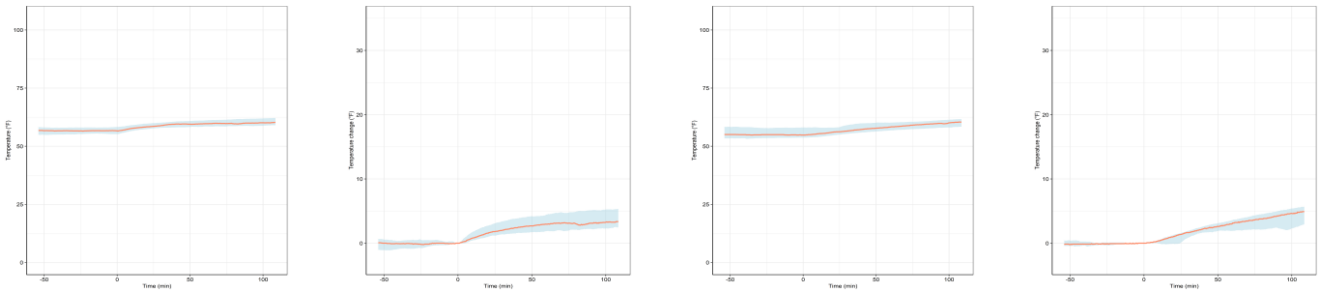
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE14 – Height: 10"



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

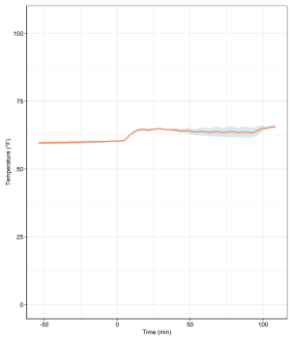
Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

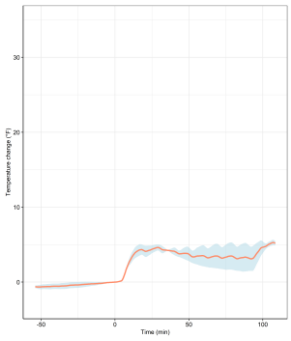
Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-13. DHE14 Temperature at various heights of the stratification tree during operation periods

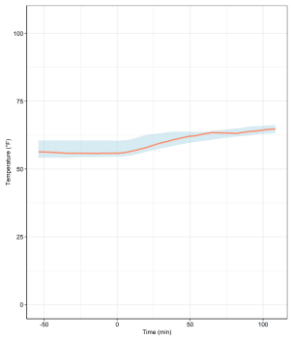
DHE14 – Temperature: Directly Heated Space



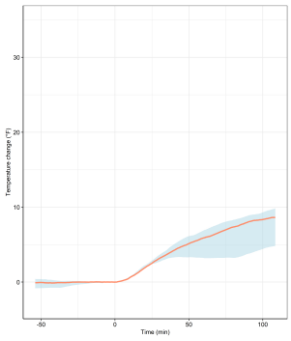
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

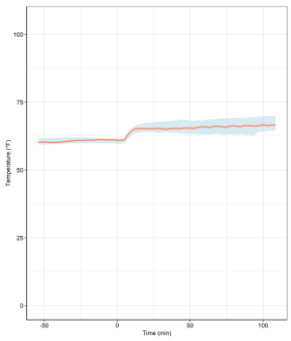


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

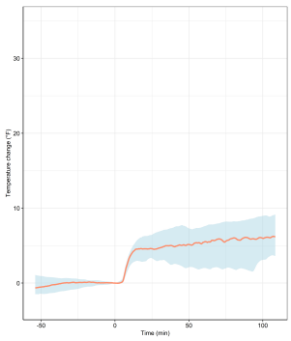


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

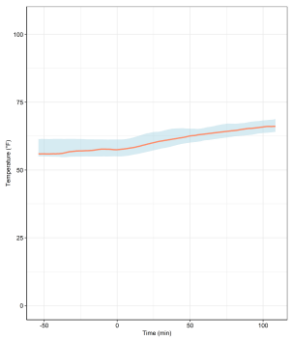
DHE14 – Temperature: Kitchen



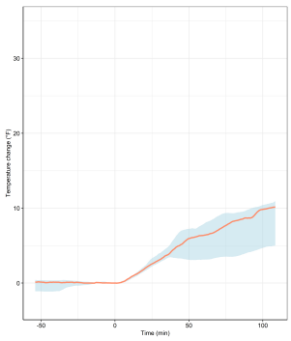
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

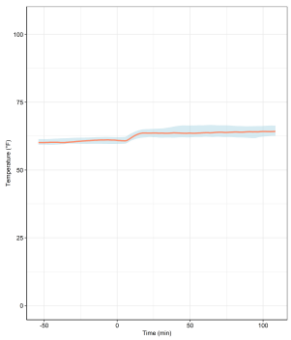


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

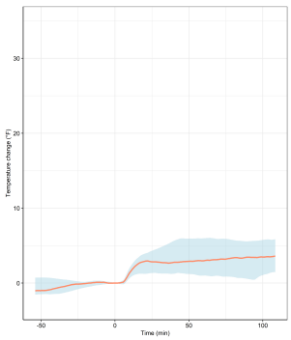


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

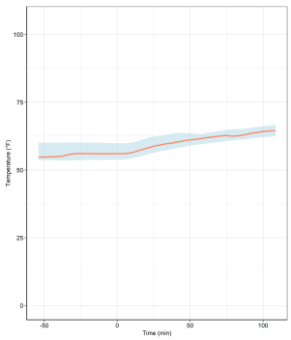
DHE14 – Temperature: Second Living Room



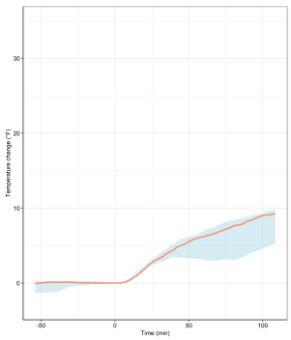
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



Temperature, High-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-14. DHE14 Temperature at different spaces in the home during operation periods

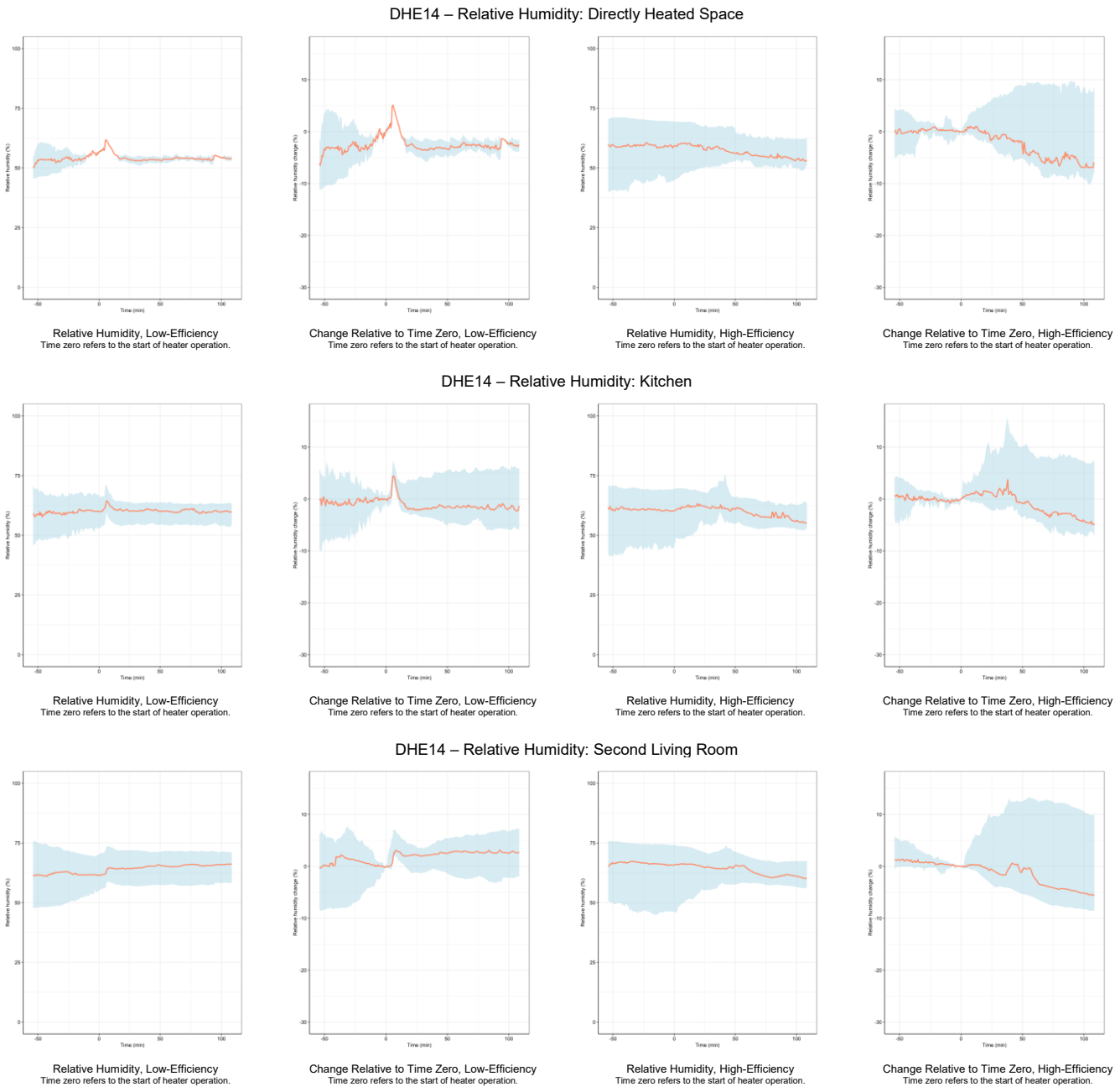
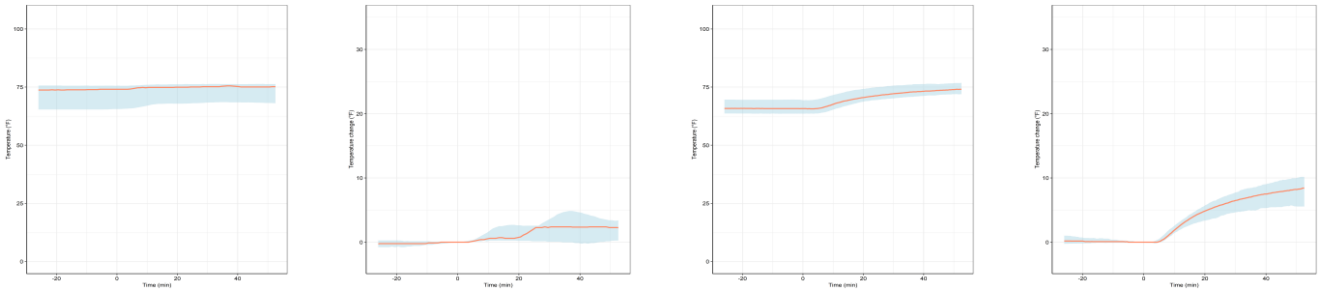


Figure B-15. DHE14 Relative Humidity in different spaces in the home during operation periods

DHE15 – Height: 67"



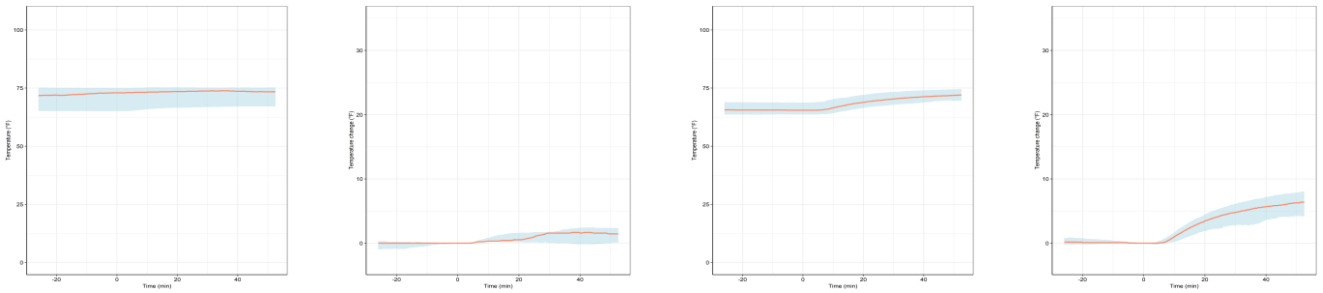
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE15 – Height: 43"



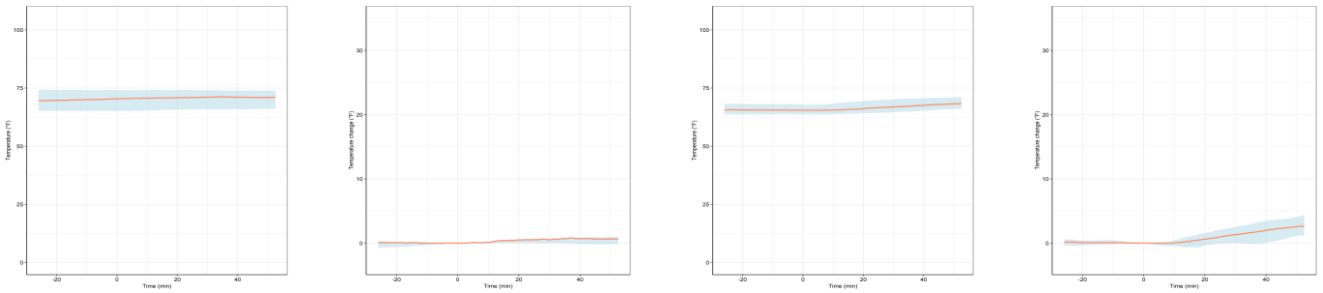
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE15 – Height: 24"



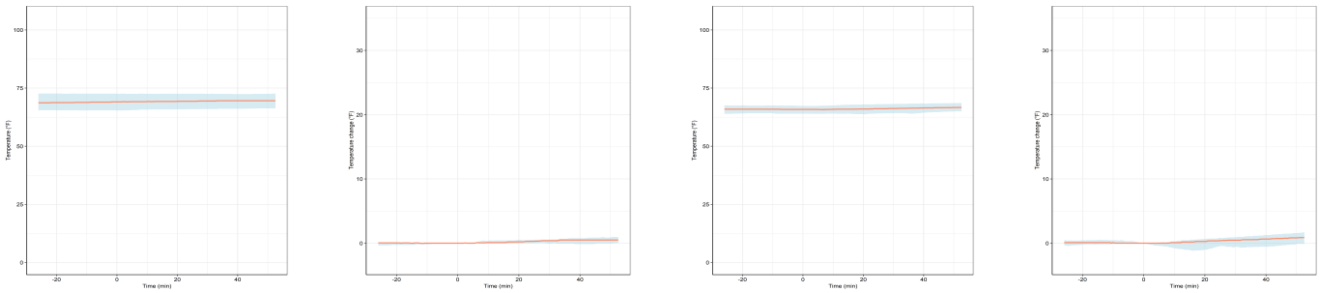
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE15 – Height: 10"



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

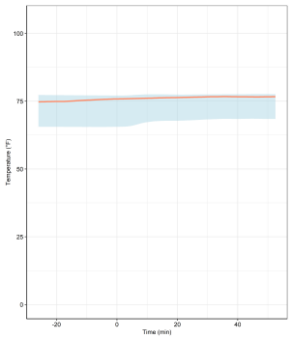
Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

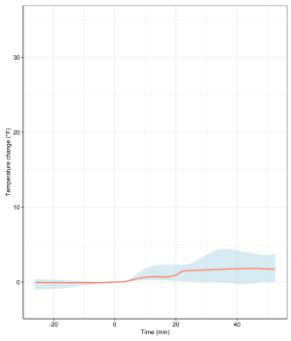
Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-16. DHE15 Temperature at various heights of the stratification tree during operation periods

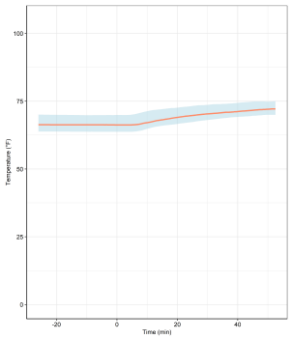
DHE15 – Temperature: Directly Heated Space



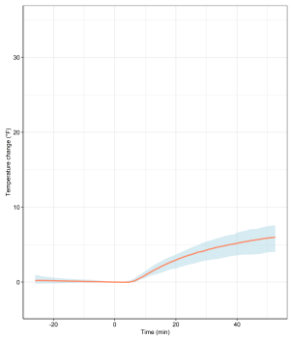
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

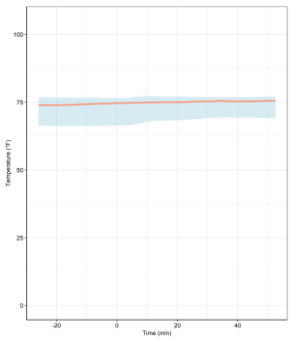


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

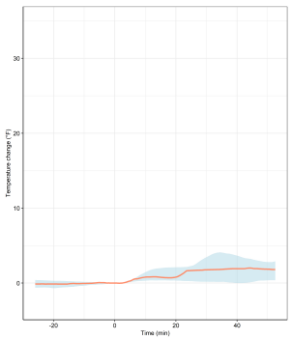


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

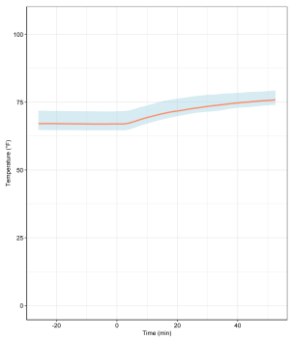
DHE15 – Temperature: Kitchen



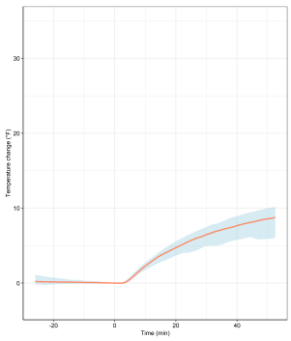
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



Temperature, High-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-17. DHE15 Temperature at different spaces in the home during operation periods

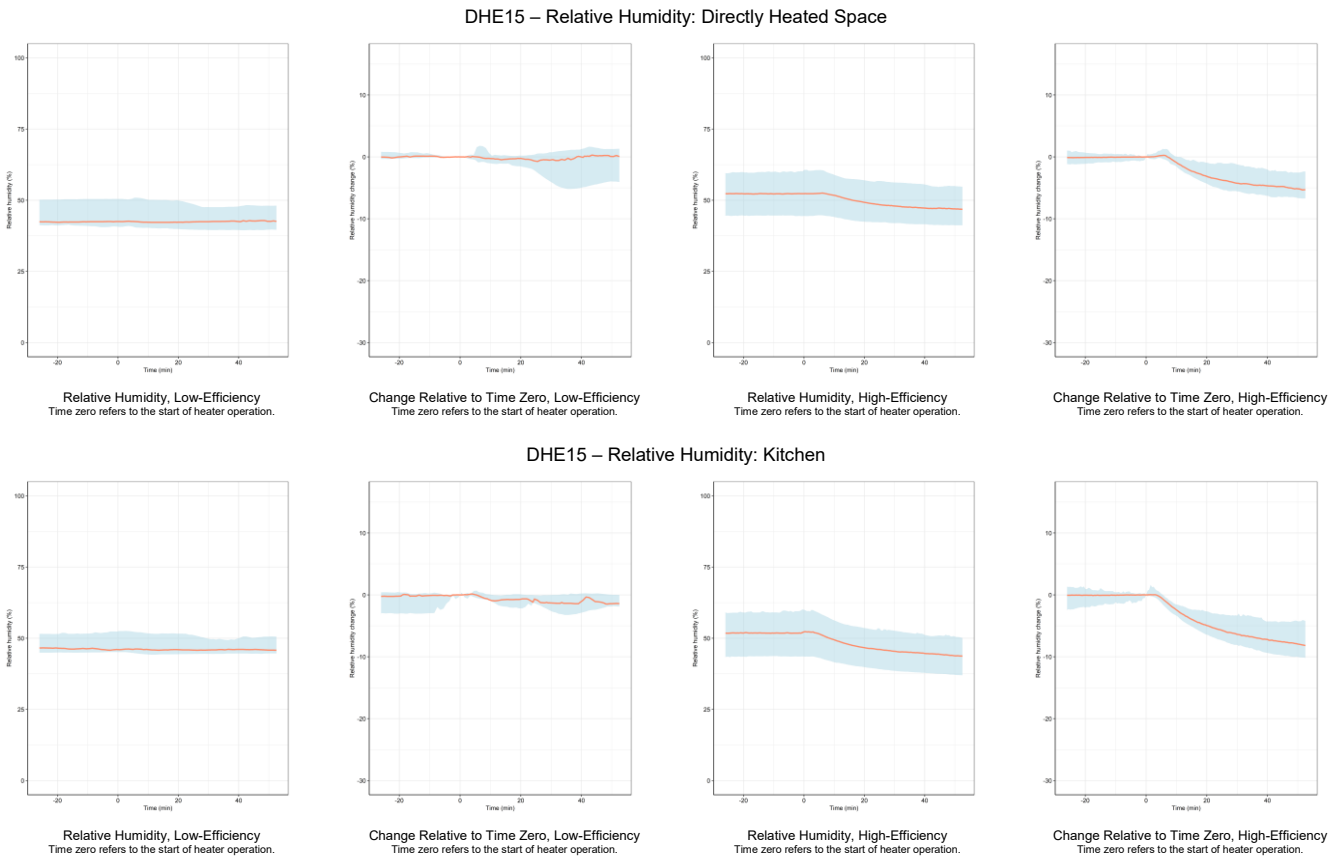
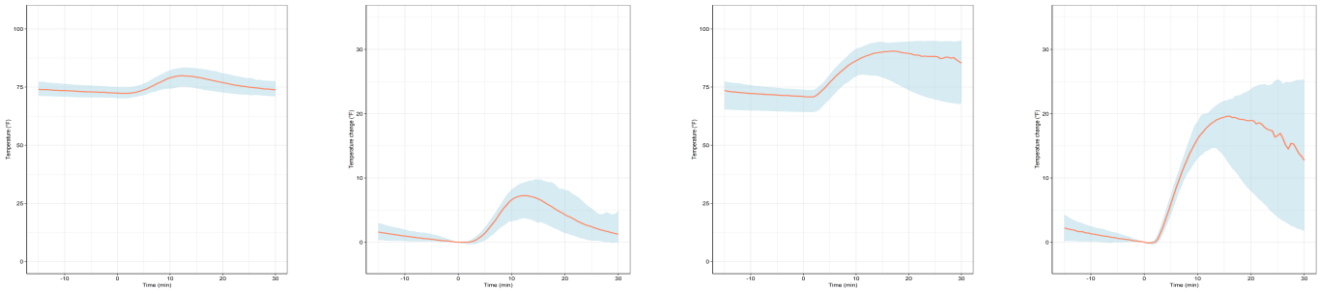


Figure B-18. DHE15 Relative Humidity in different spaces in the home during operation periods

DHE16 – Height: 67"



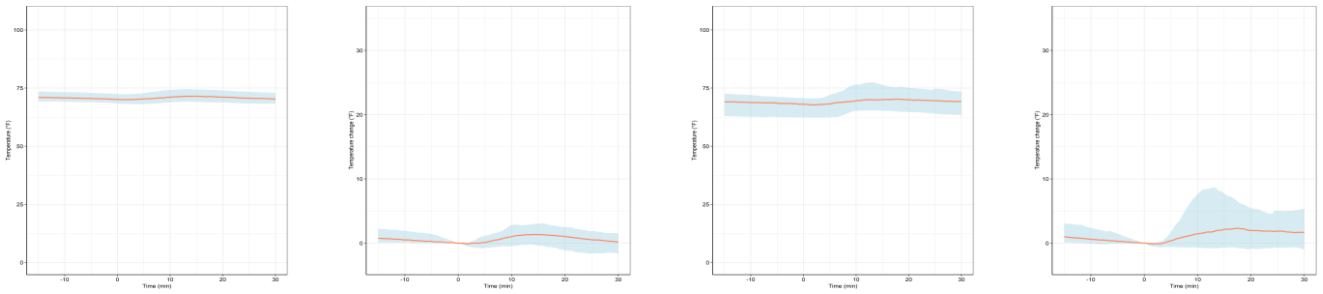
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE16 – Height: 43"



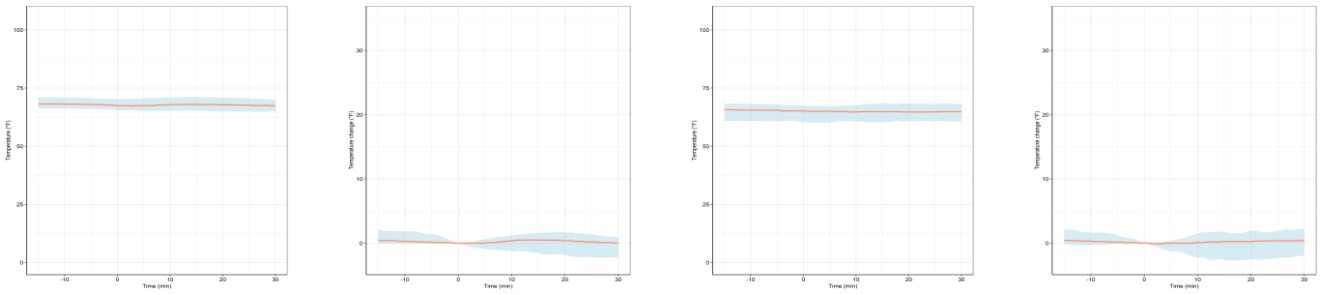
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE16 – Height: 24"



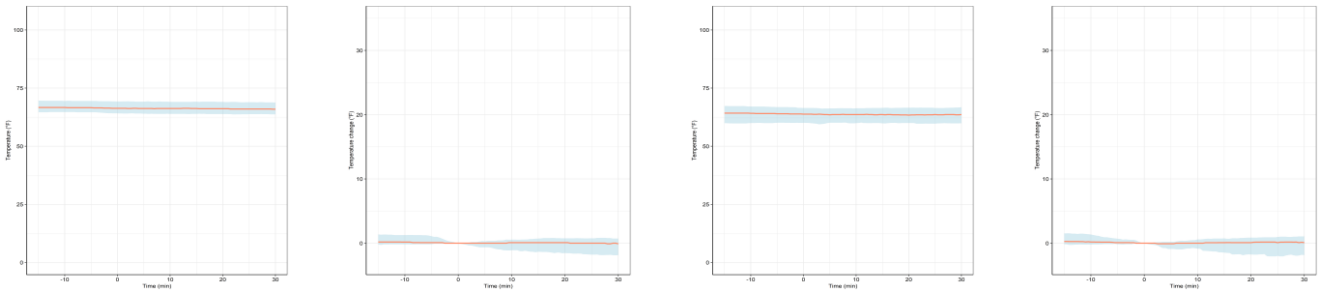
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE16 – Height: 10"



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

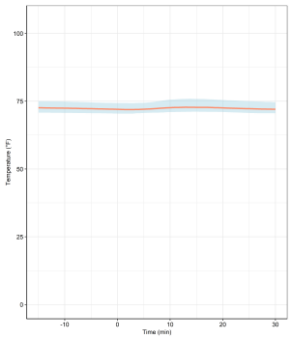
Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

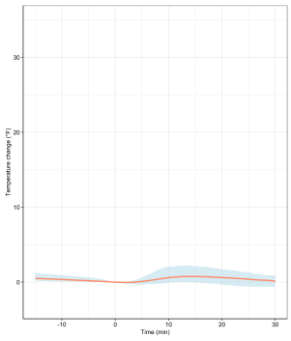
Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-19. DHE16 Temperature at various heights of the stratification tree during operation periods

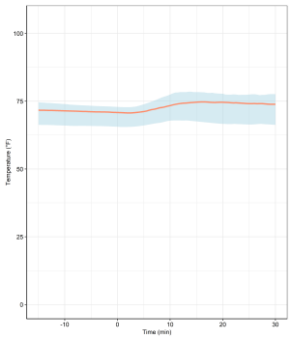
DHE16 – Temperature: Directly Heated Space



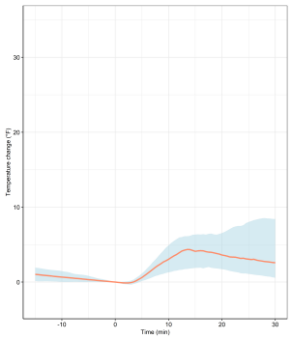
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

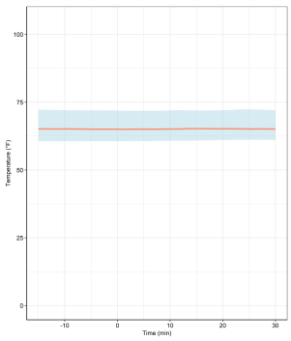


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

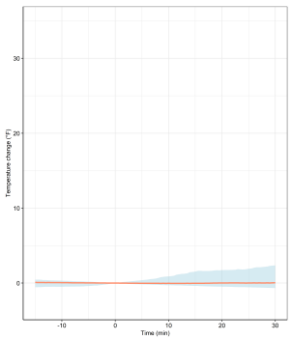


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

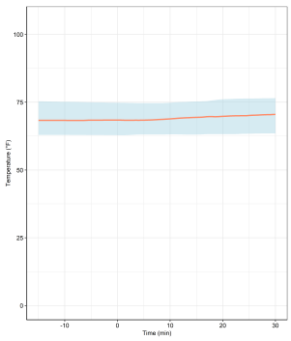
DHE16 – Temperature: Kitchen



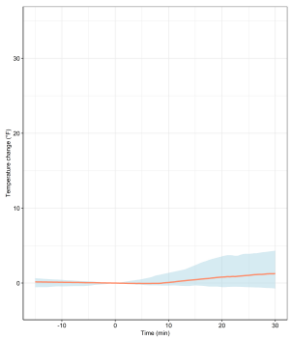
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

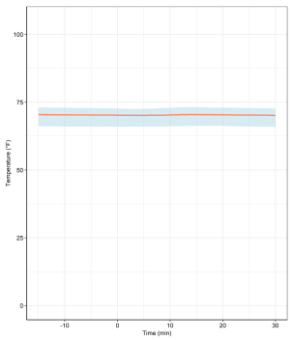


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

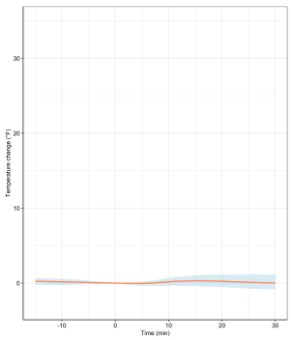


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

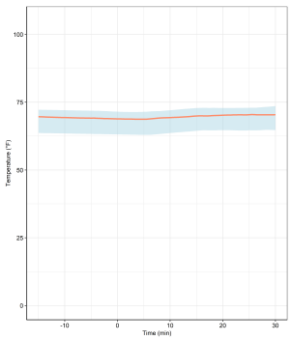
DHE16 – Temperature: Bedroom



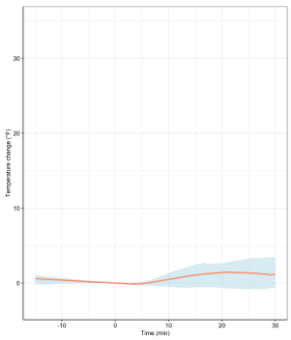
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



Temperature, High-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-20. DHE16 Temperature at different spaces in the home during operation periods

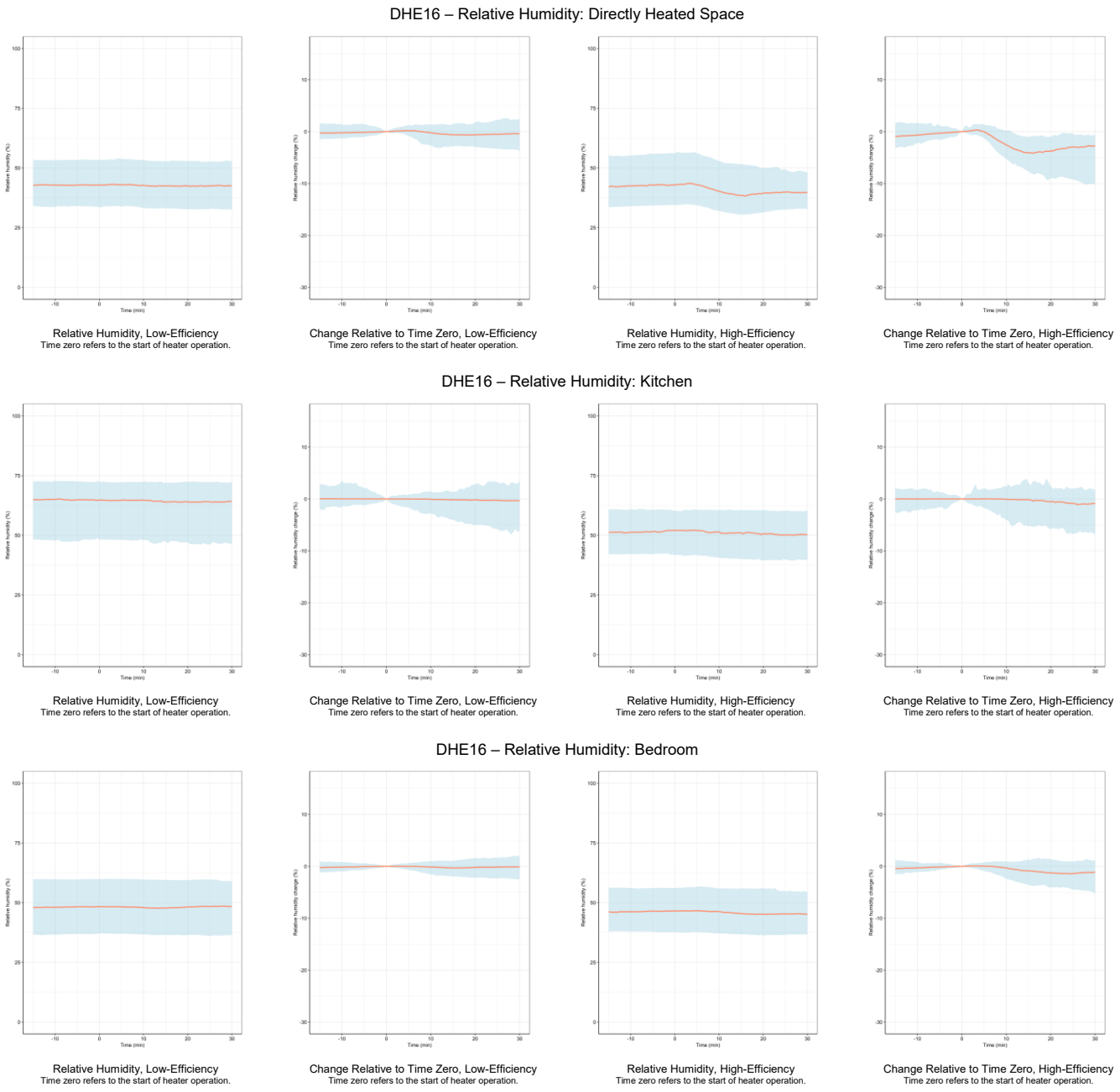
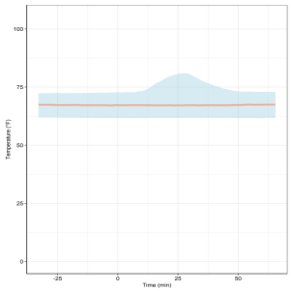
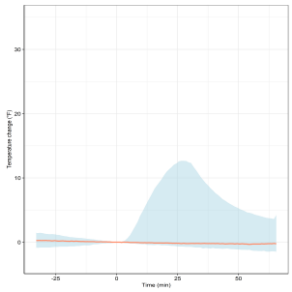


Figure B-21. DHE16 Relative Humidity in different spaces in the home during operation periods

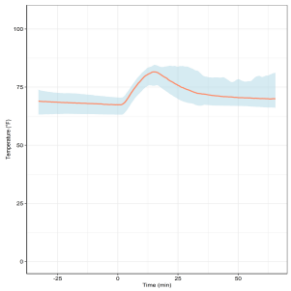
DHE18 – Height: 67"



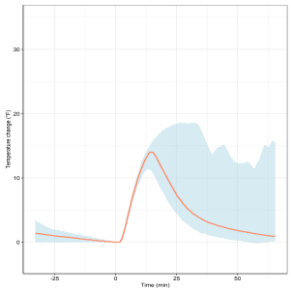
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

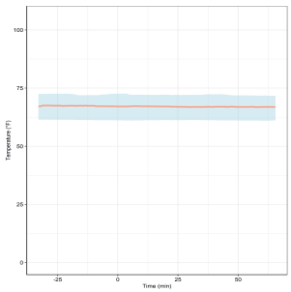


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

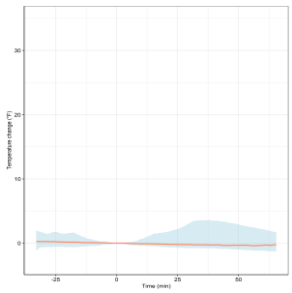


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

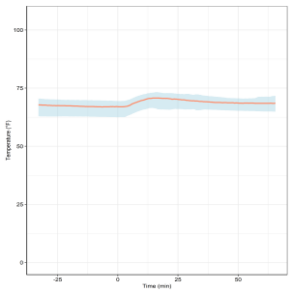
DHE18 – Height: 43"



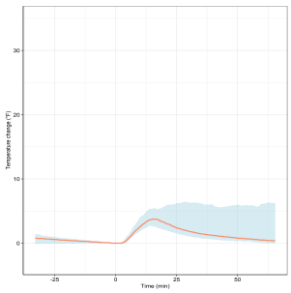
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

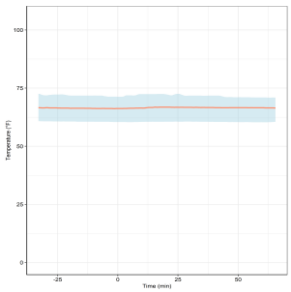


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

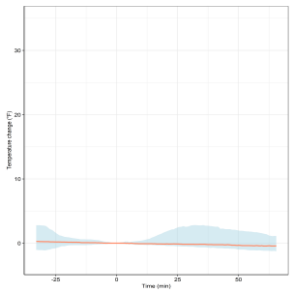


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

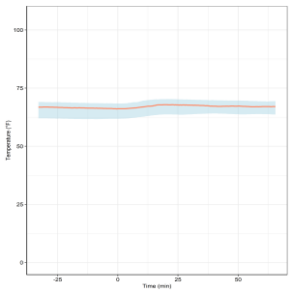
DHE18 – Height: 24"



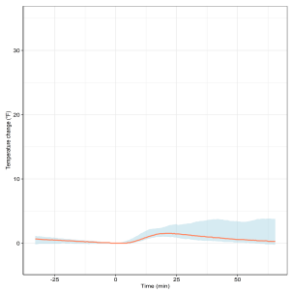
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

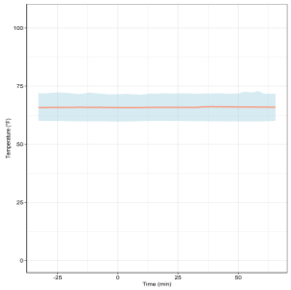


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

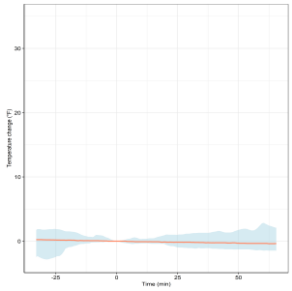


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

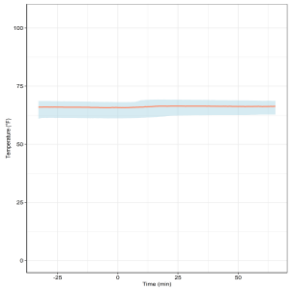
DHE18 – Height: 10"



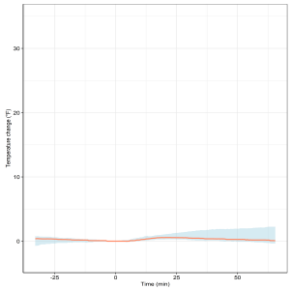
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



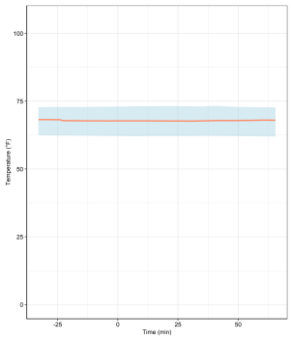
Temperature, High-Efficiency
Time zero refers to the start of heater operation.



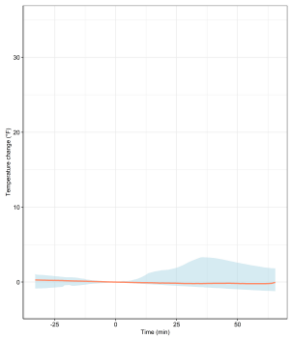
Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-22. DHE18 Temperature at various heights of the stratification tree during operation periods

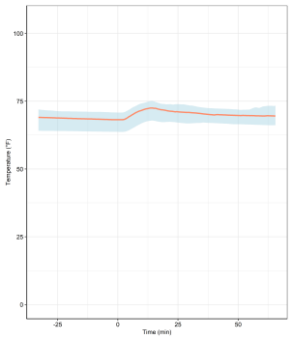
DHE18 – Temperature: Directly Heated Space



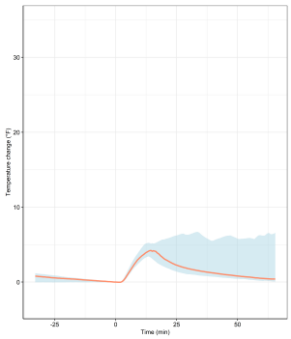
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

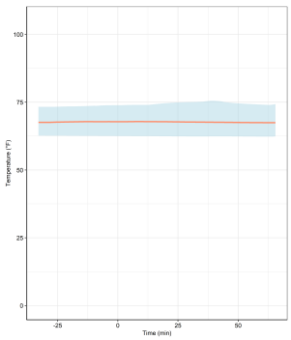


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

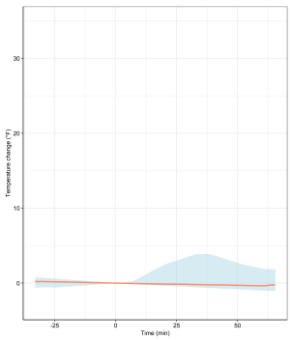


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

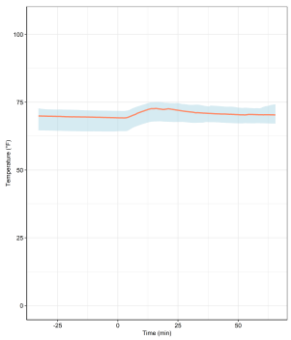
DHE18 – Temperature: Kitchen



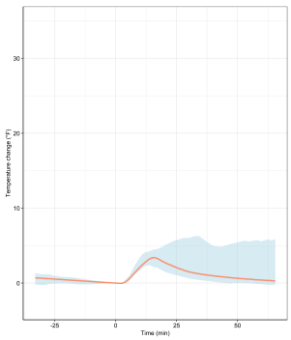
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

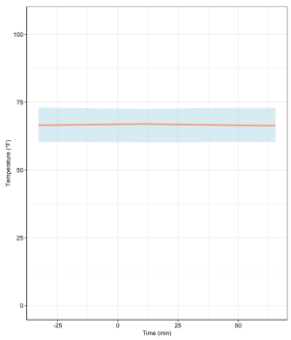


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

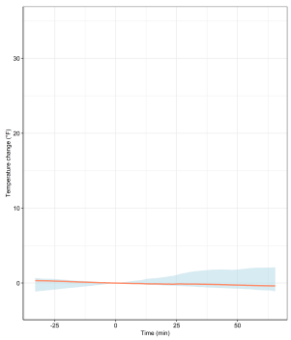


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

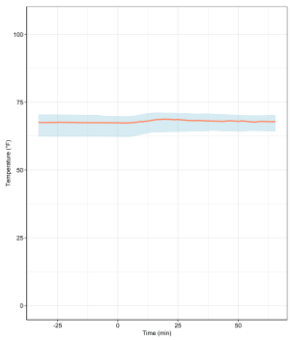
DHE18 – Temperature: Bedroom



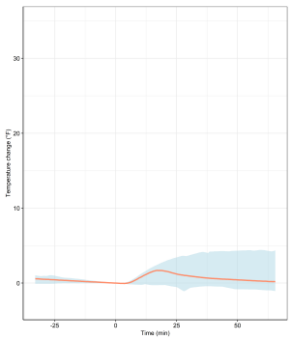
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



Temperature, High-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-23. DHE18 Temperature at different spaces in the home during operation periods

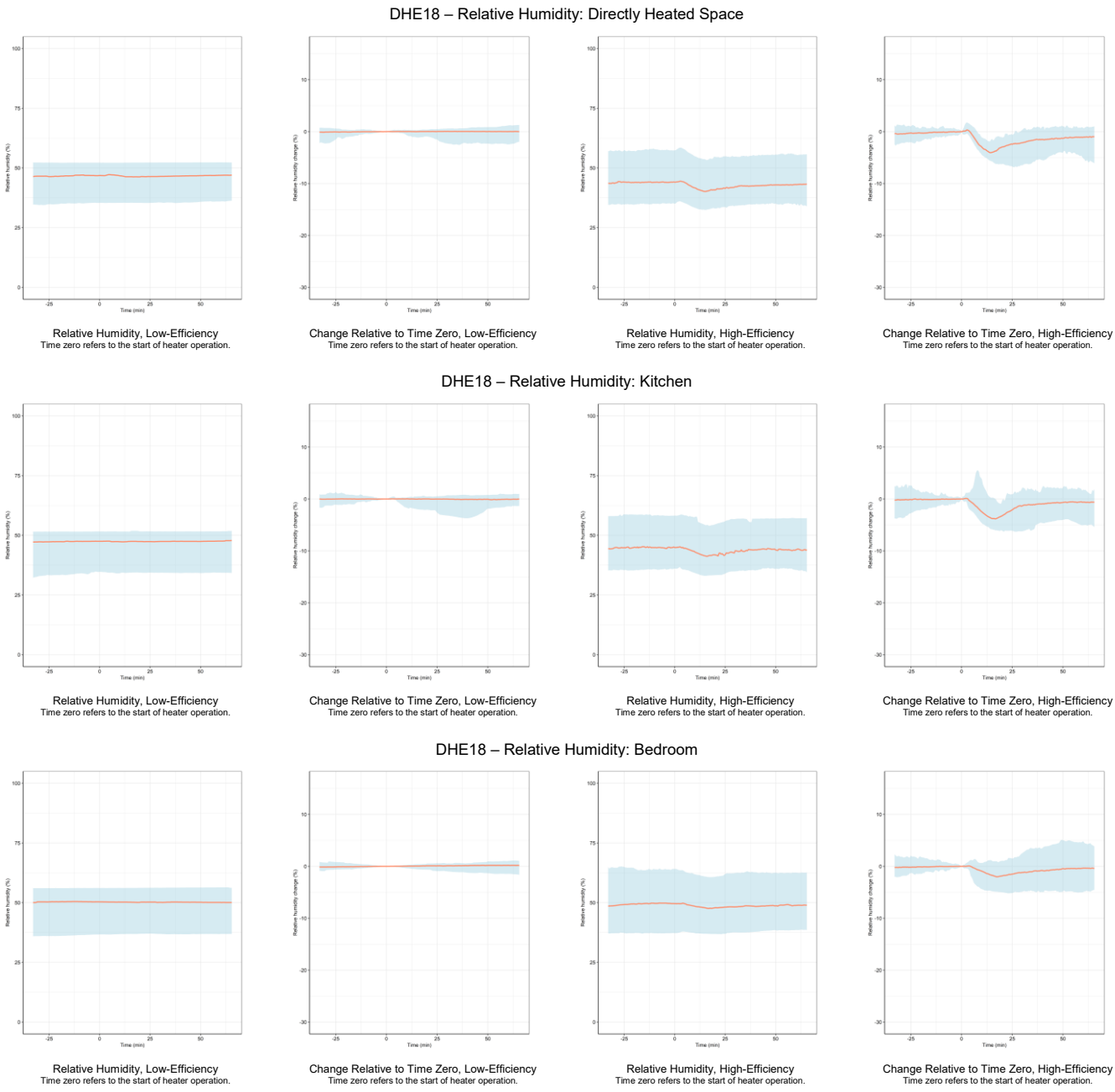
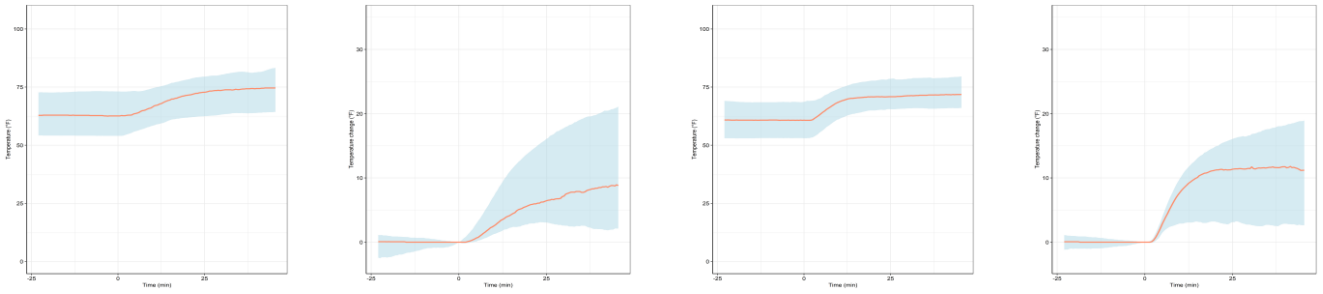


Figure B-24. DHE18 Relative Humidity in different spaces in the home during operation periods

DHE19 – Height: 67"



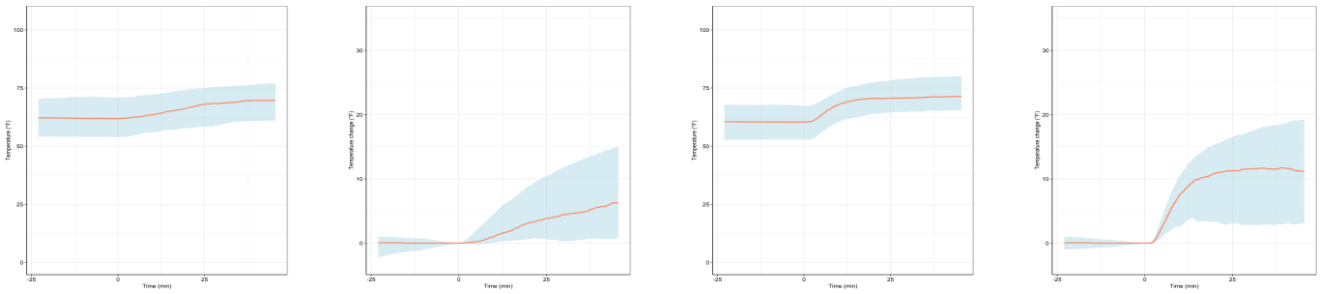
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE19 – Height: 43"



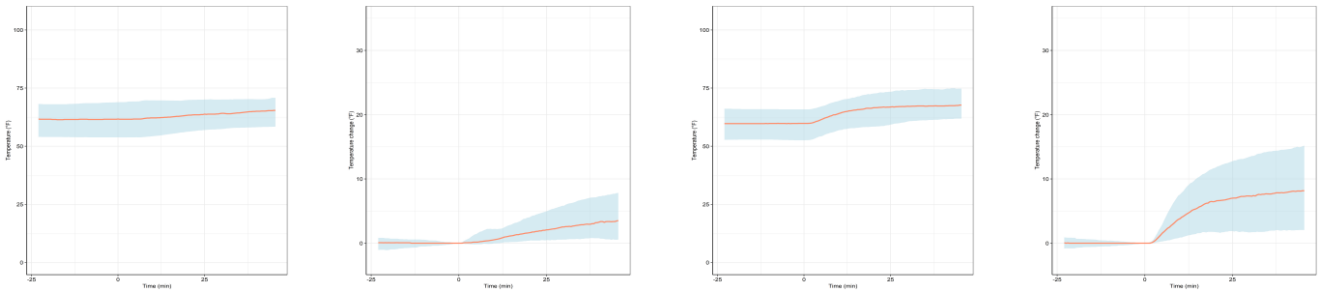
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE19 – Height: 24"



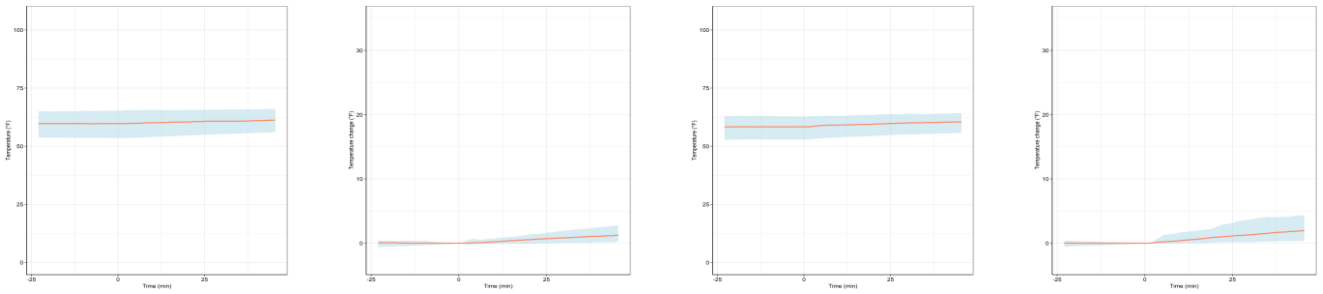
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE19 – Height: 10"



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-25. DHE19 Temperature at various heights of the stratification tree during operation periods

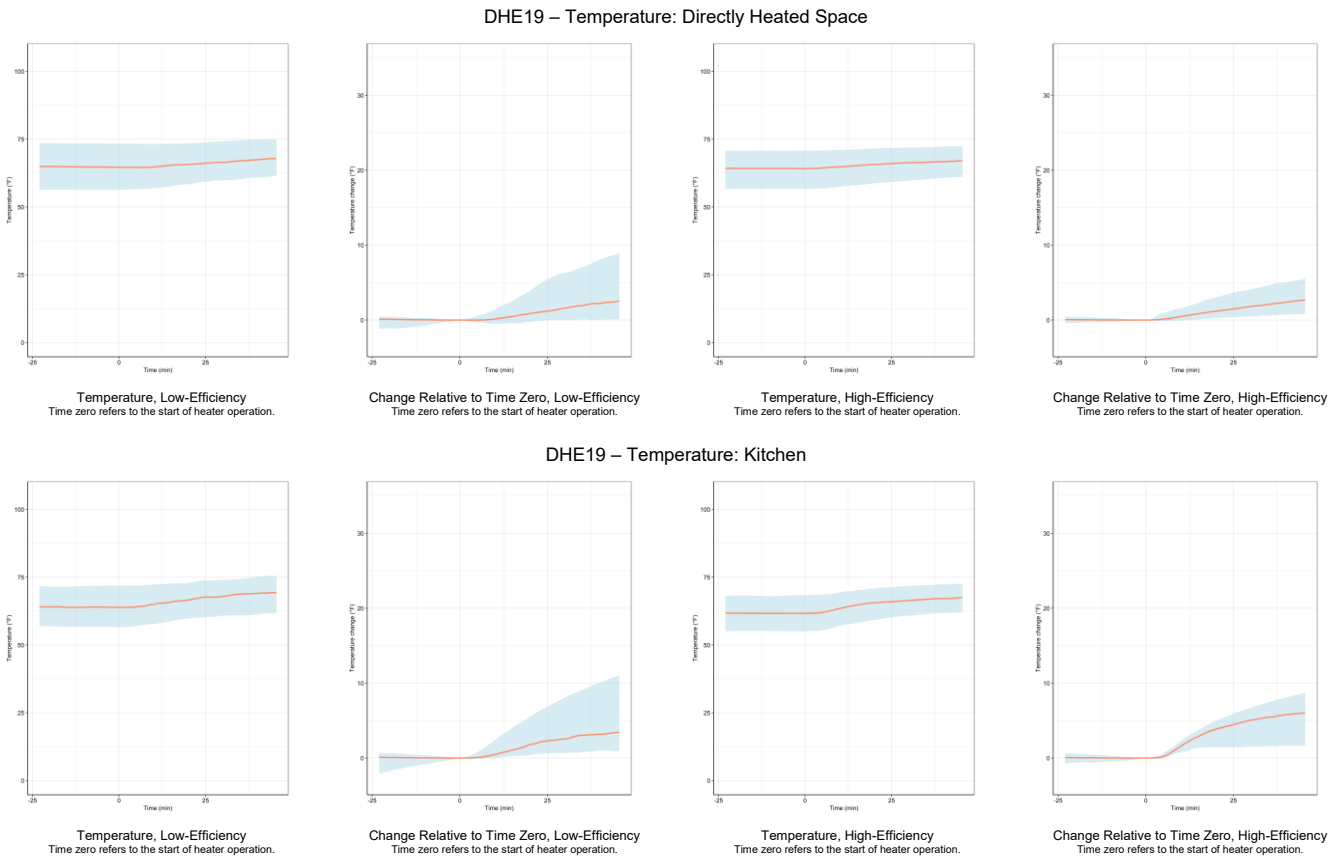


Figure B-26. DHE19 Temperature at different spaces in the home during operation periods

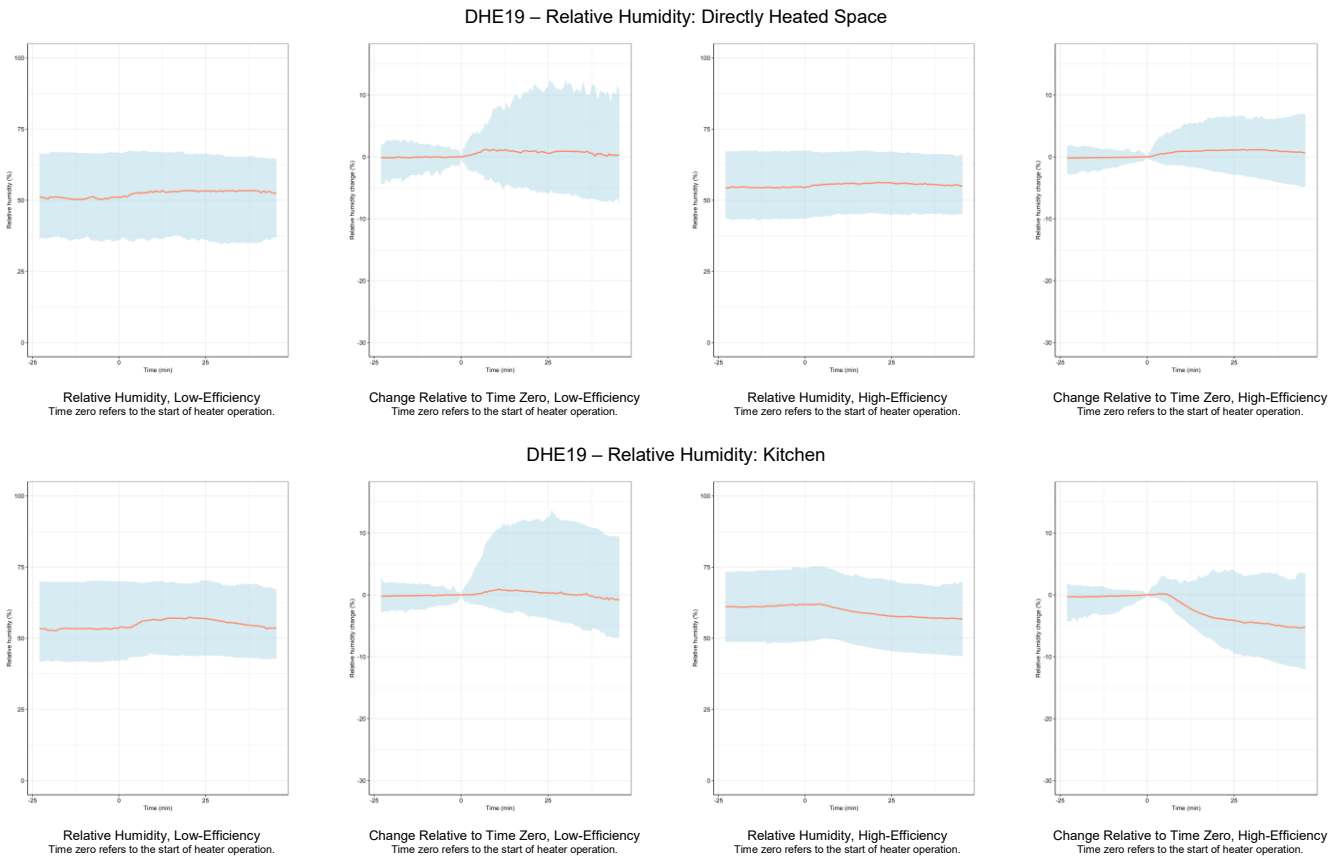
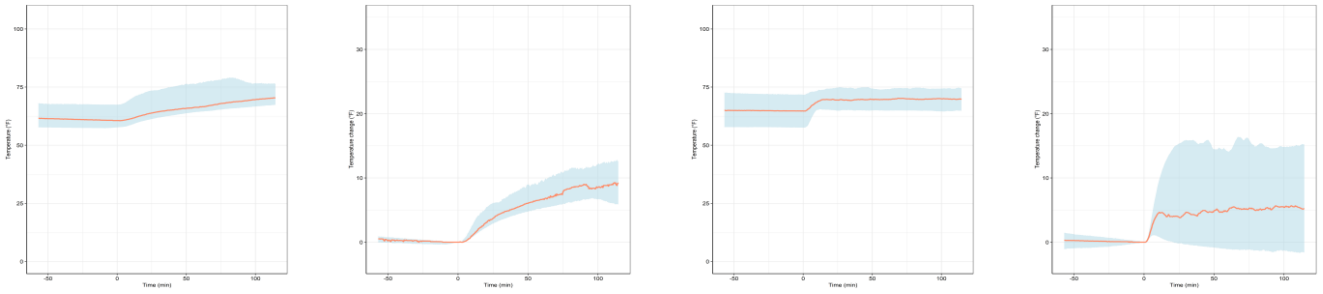


Figure B-27. DHE19 Relative Humidity in different spaces in the home during operation periods

DHE22 – Height: 67"



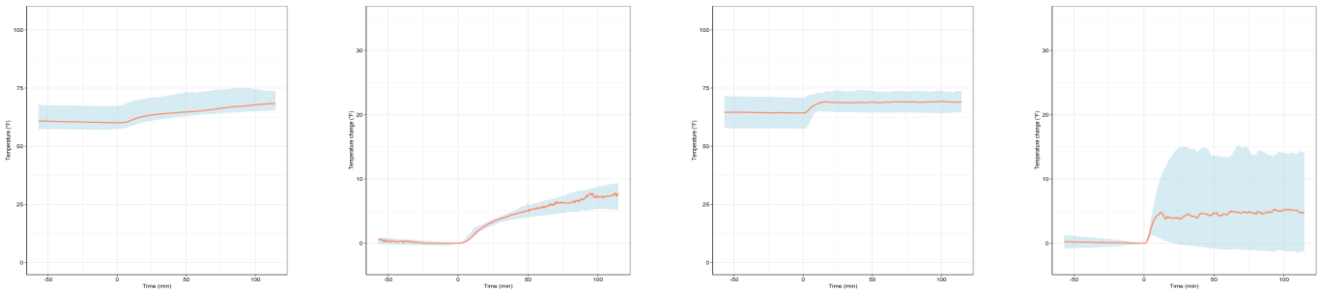
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE22 – Height: 43"



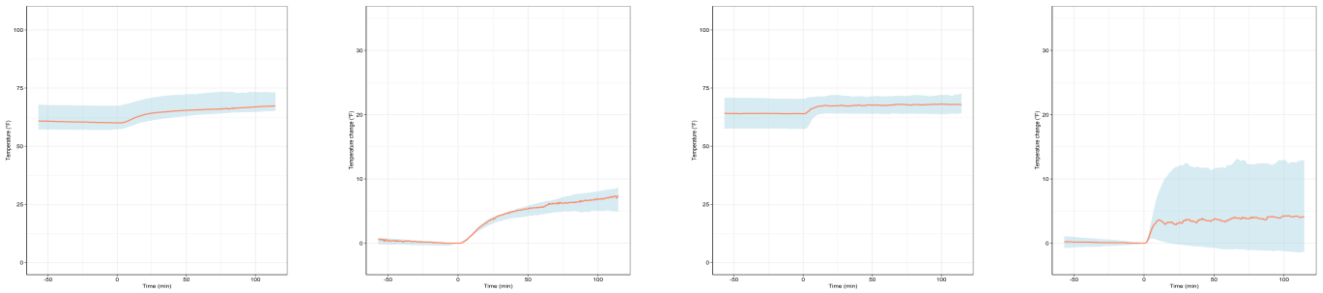
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE22 – Height: 24"



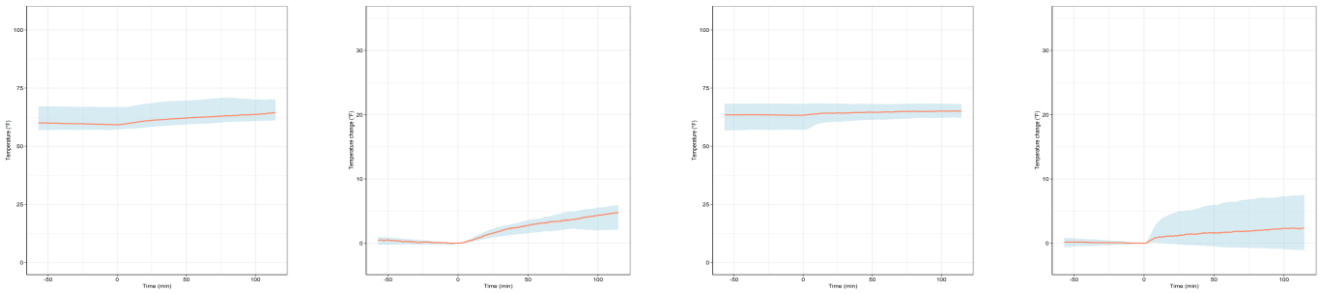
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE22 – Height: 10"



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

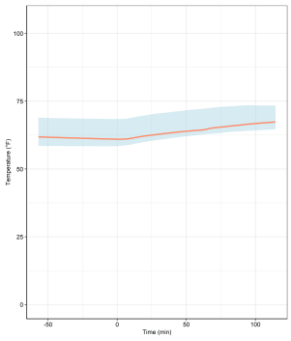
Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Temperature, High-Efficiency
Time zero refers to the start of heater operation.

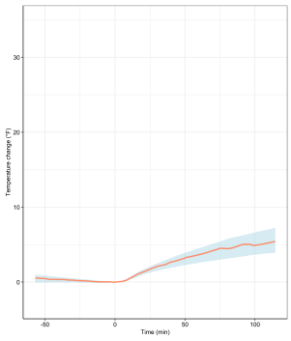
Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-28. DHE22 Temperature at various heights of the stratification tree during operation periods

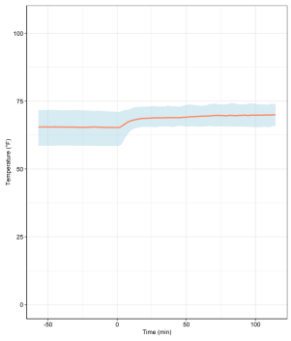
DHE22 – Temperature: Directly Heated Space



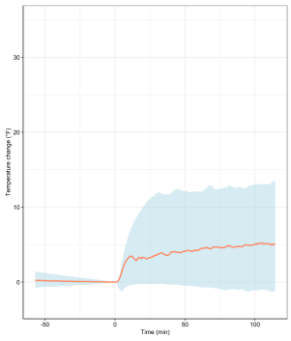
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

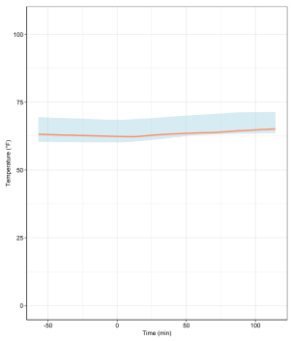


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

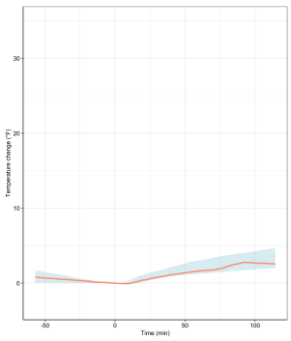


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

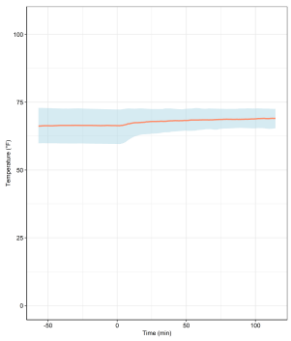
DHE22 – Temperature: Kitchen



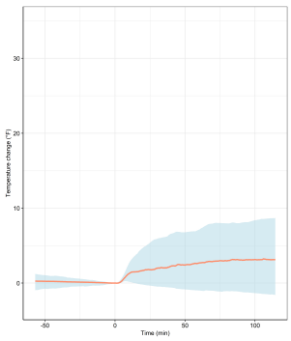
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

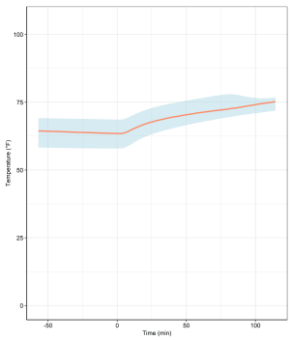


Temperature, High-Efficiency
Time zero refers to the start of heater operation.

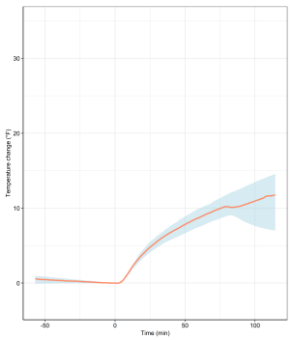


Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

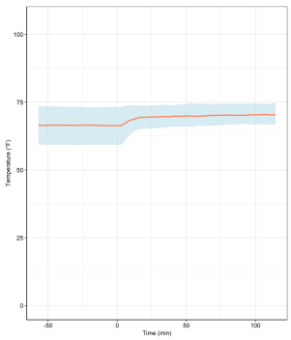
DHE22 – Temperature: Bedroom



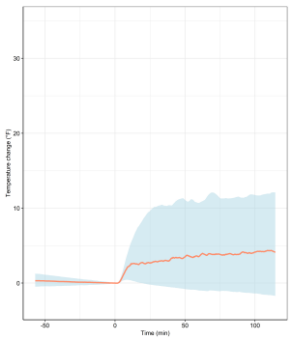
Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.



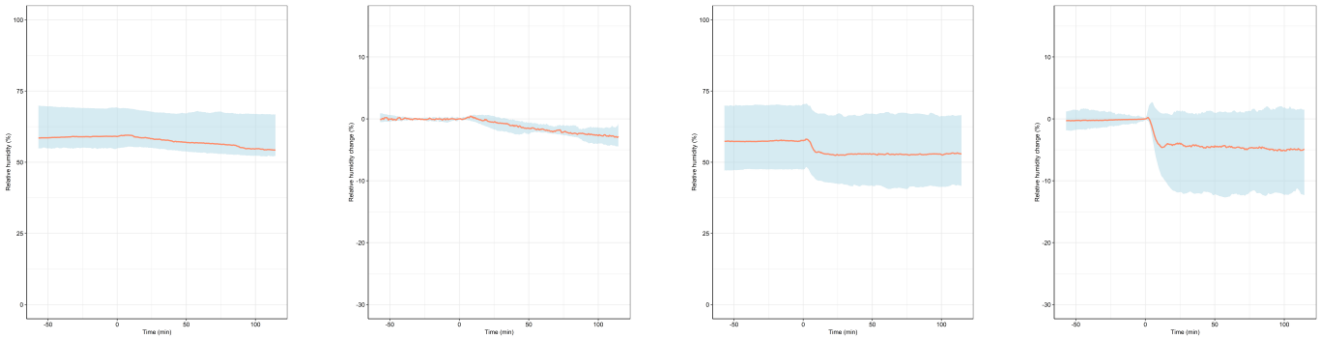
Temperature, High-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-29. DHE22 Temperature at different spaces in the home during operation periods

DHE22 – Relative Humidity: Directly Heated Space



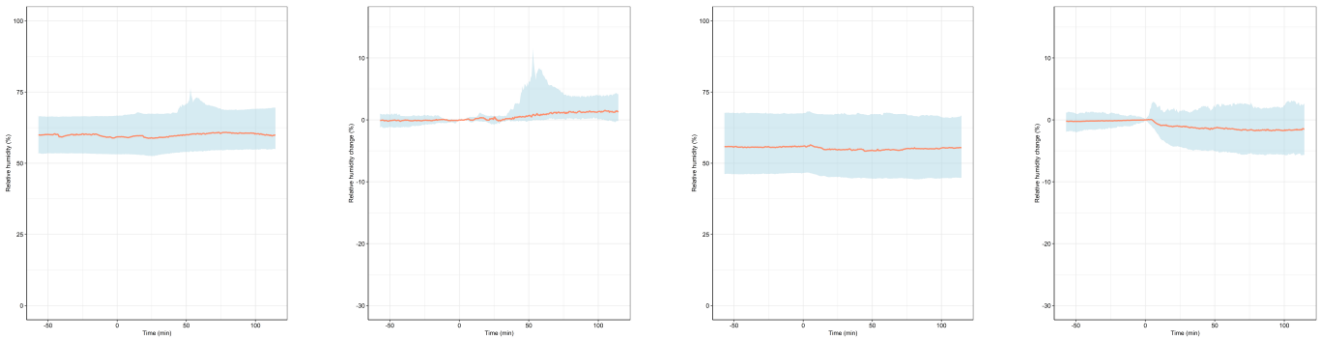
Relative Humidity, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Relative Humidity, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE22 – Relative Humidity: Kitchen



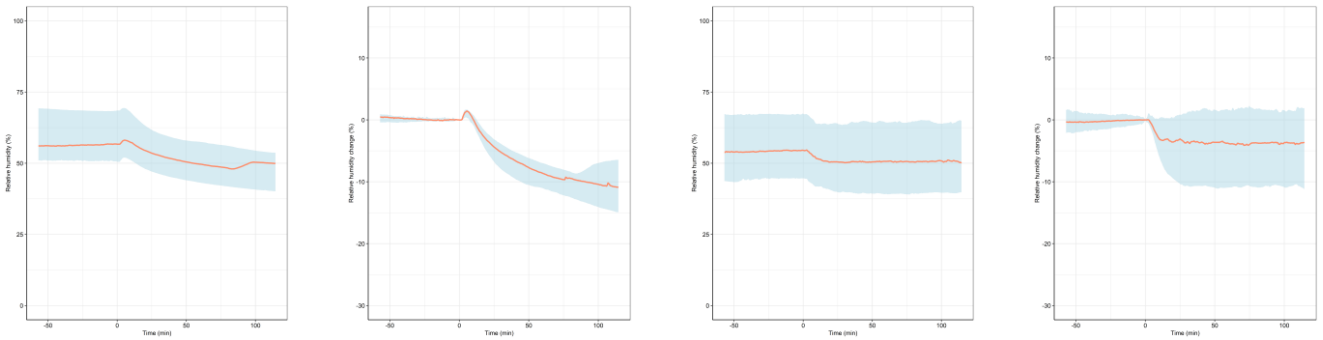
Relative Humidity, Low-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Relative Humidity, High-Efficiency
Time zero refers to the start of heater operation.

Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

DHE22 – Relative Humidity: Bedroom



Relative Humidity, Low-Efficiency
Time zero refers to the start of heater operation.

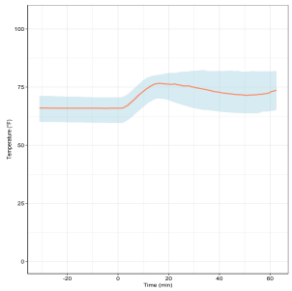
Change Relative to Time Zero, Low-Efficiency
Time zero refers to the start of heater operation.

Relative Humidity, High-Efficiency
Time zero refers to the start of heater operation.

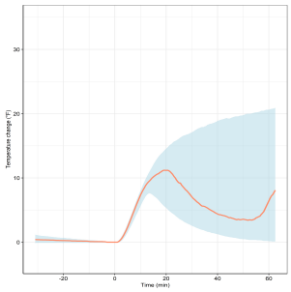
Change Relative to Time Zero, High-Efficiency
Time zero refers to the start of heater operation.

Figure B-30. DHE22 Relative Humidity in different spaces in the home during operation periods

DHEFF – Height: 67"

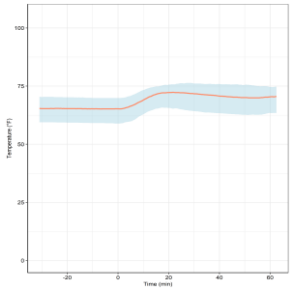


Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

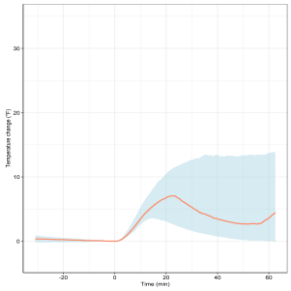


Change Relative to Time Zero, Low-Efficiency
Time zero refers to the end of heater operation.

DHEFF – Height: 43"

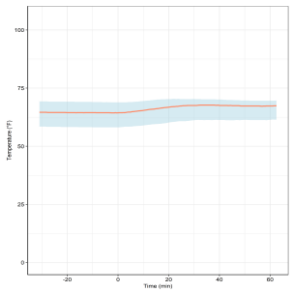


Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

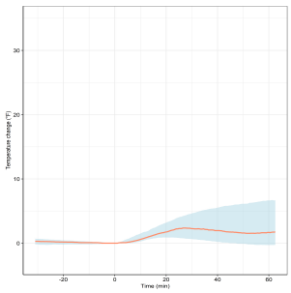


Change Relative to Time Zero, Low-Efficiency
Time zero refers to the end of heater operation.

DHEFF – Height: 24"

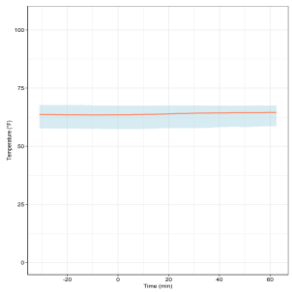


Temperature, Low-Efficiency
Time zero refers to the start of heater operation.

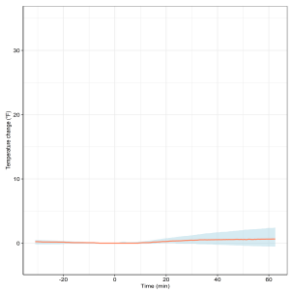


Change Relative to Time Zero, Low-Efficiency
Time zero refers to the end of heater operation.

DHEFF – Height: 10"



Temperature, Low-Efficiency
Time zero refers to the start of heater operation.



Change Relative to Time Zero, Low-Efficiency
Time zero refers to the end of heater operation.

Figure B-31. DHEFF Temperature at various heights of the stratification tree during operation periods

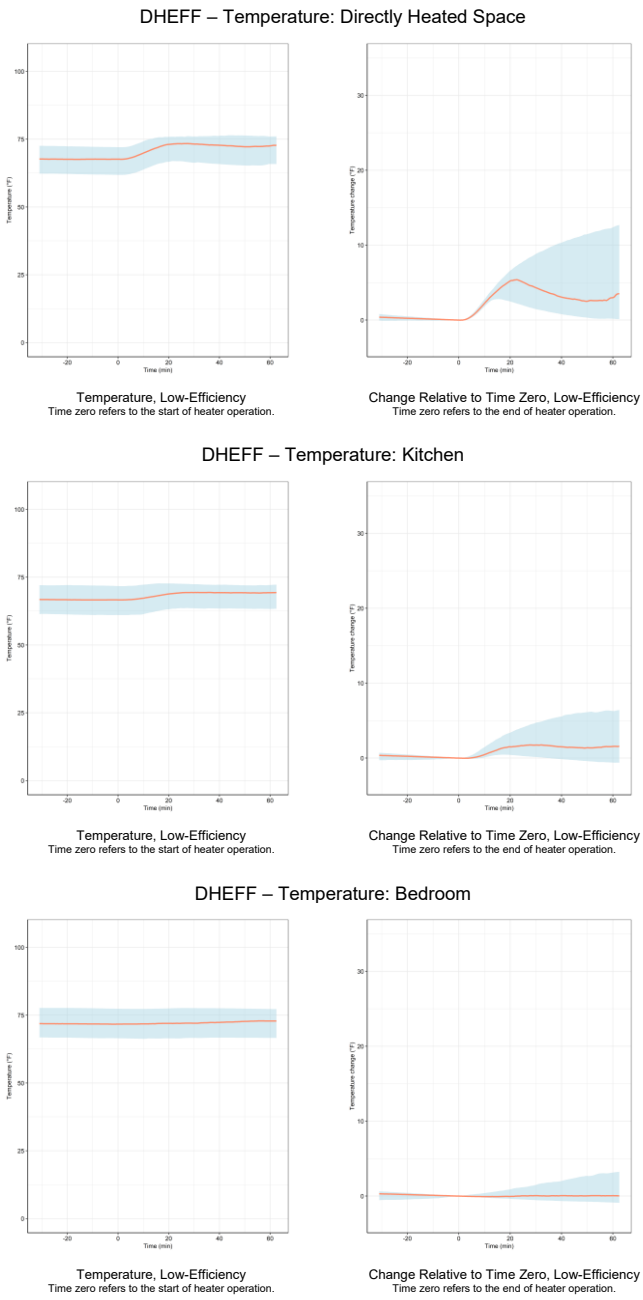


Figure B-32. DHEFF Temperature at different spaces in the home during operation periods

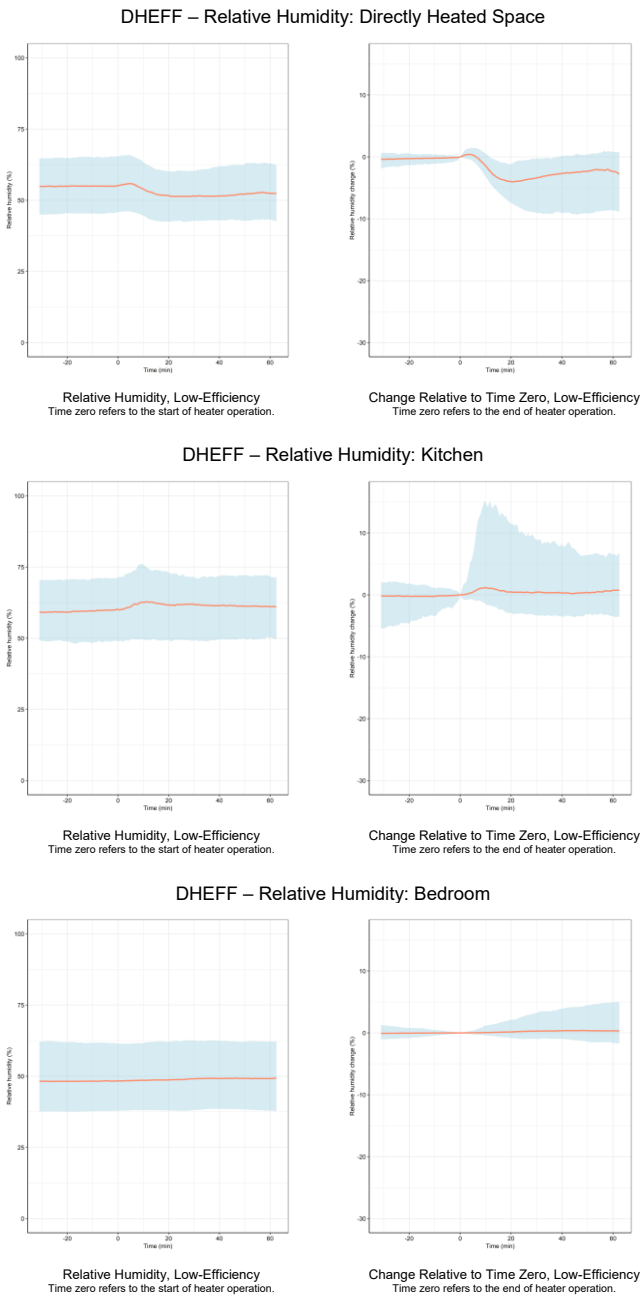


Figure B-33. DHEFF Relative Humidity in different spaces in the home during operation periods

Appendix C: CO_2 Concentration in Direct-Heated Spaces During Operation and Non-Operation

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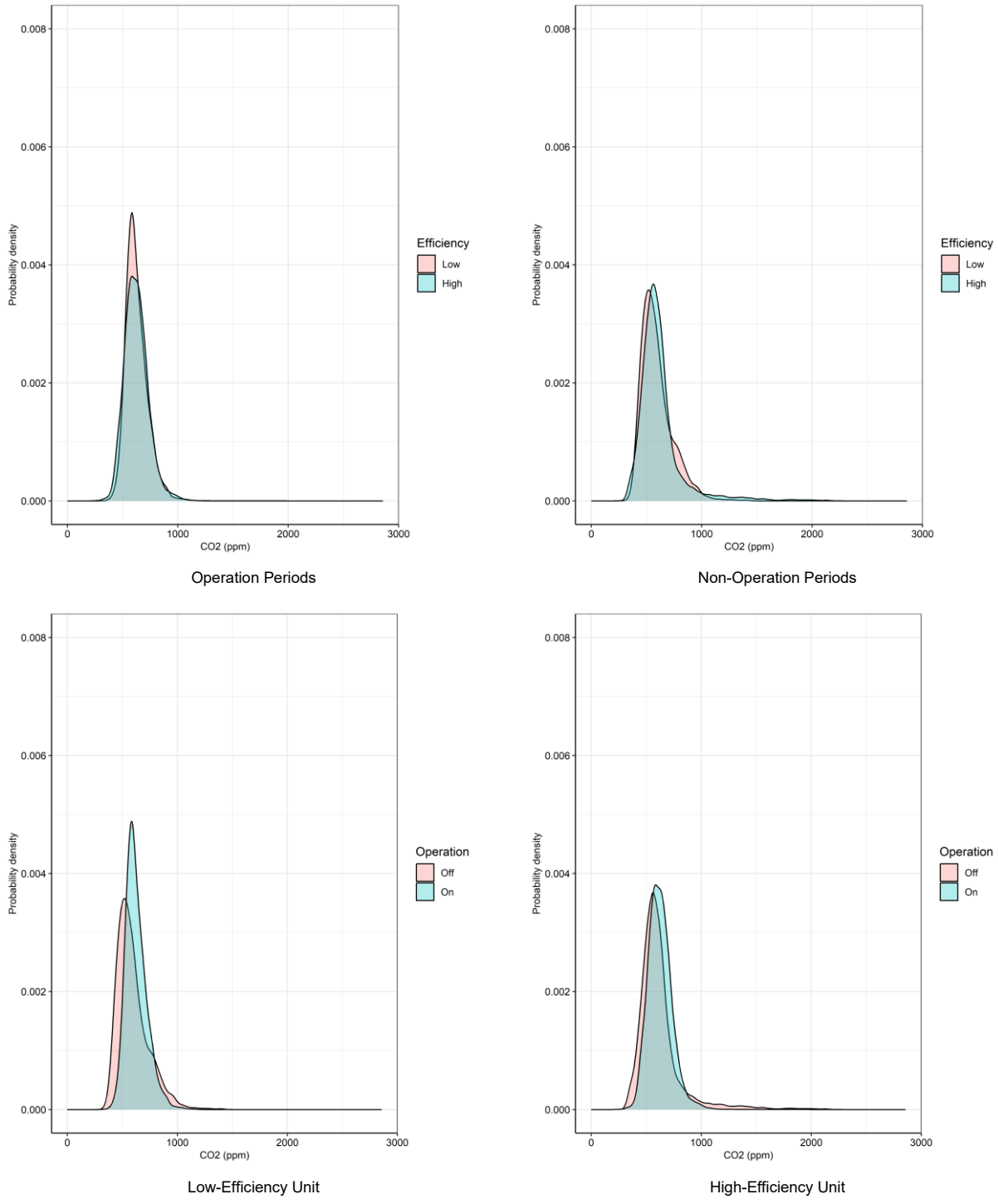

Figure C-1. DHE01 Distributions of CO_2 concentrations during operation and non-operation

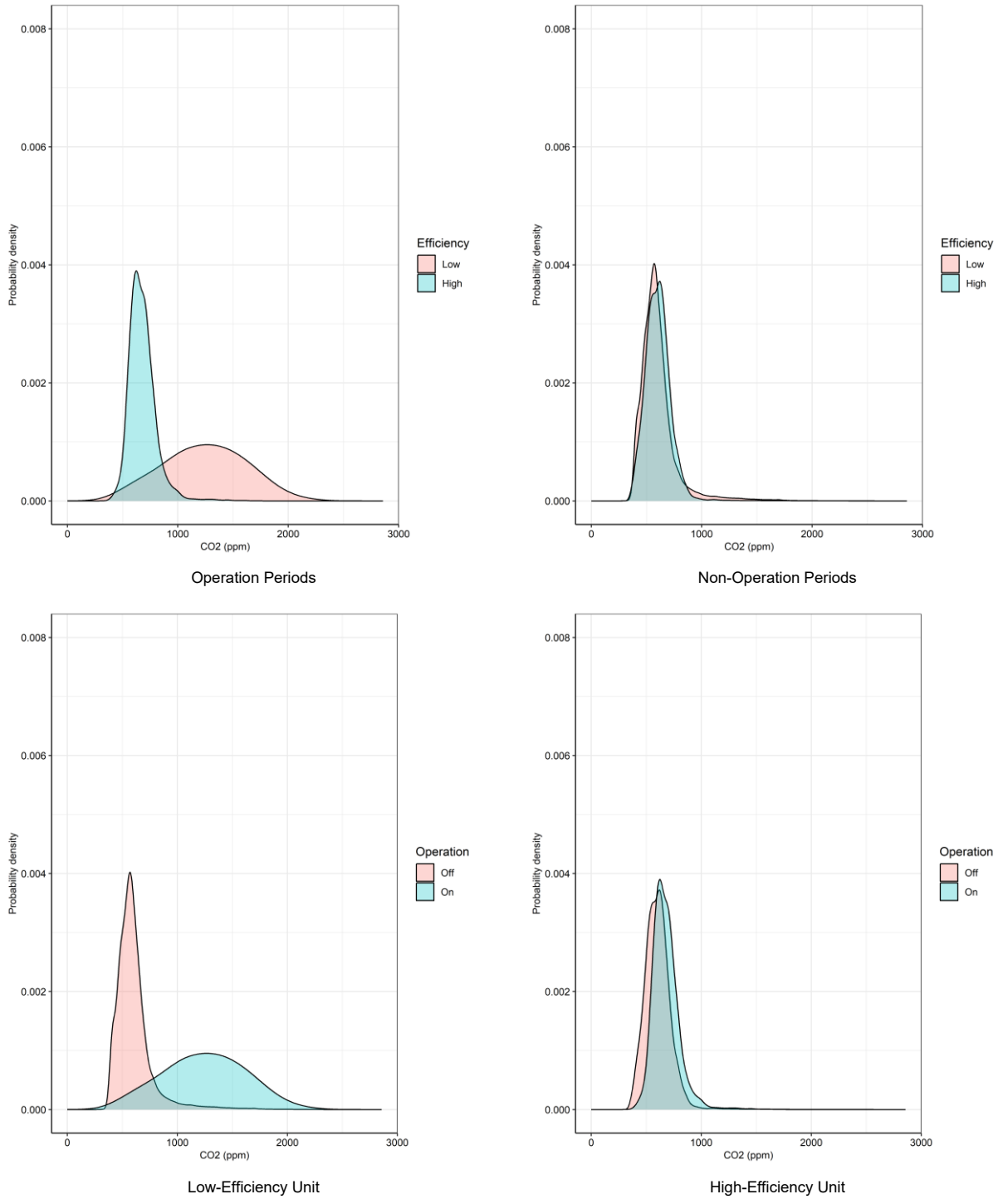

Figure C-2. DHE05 Distributions of CO_2 concentrations during operation and non-operation

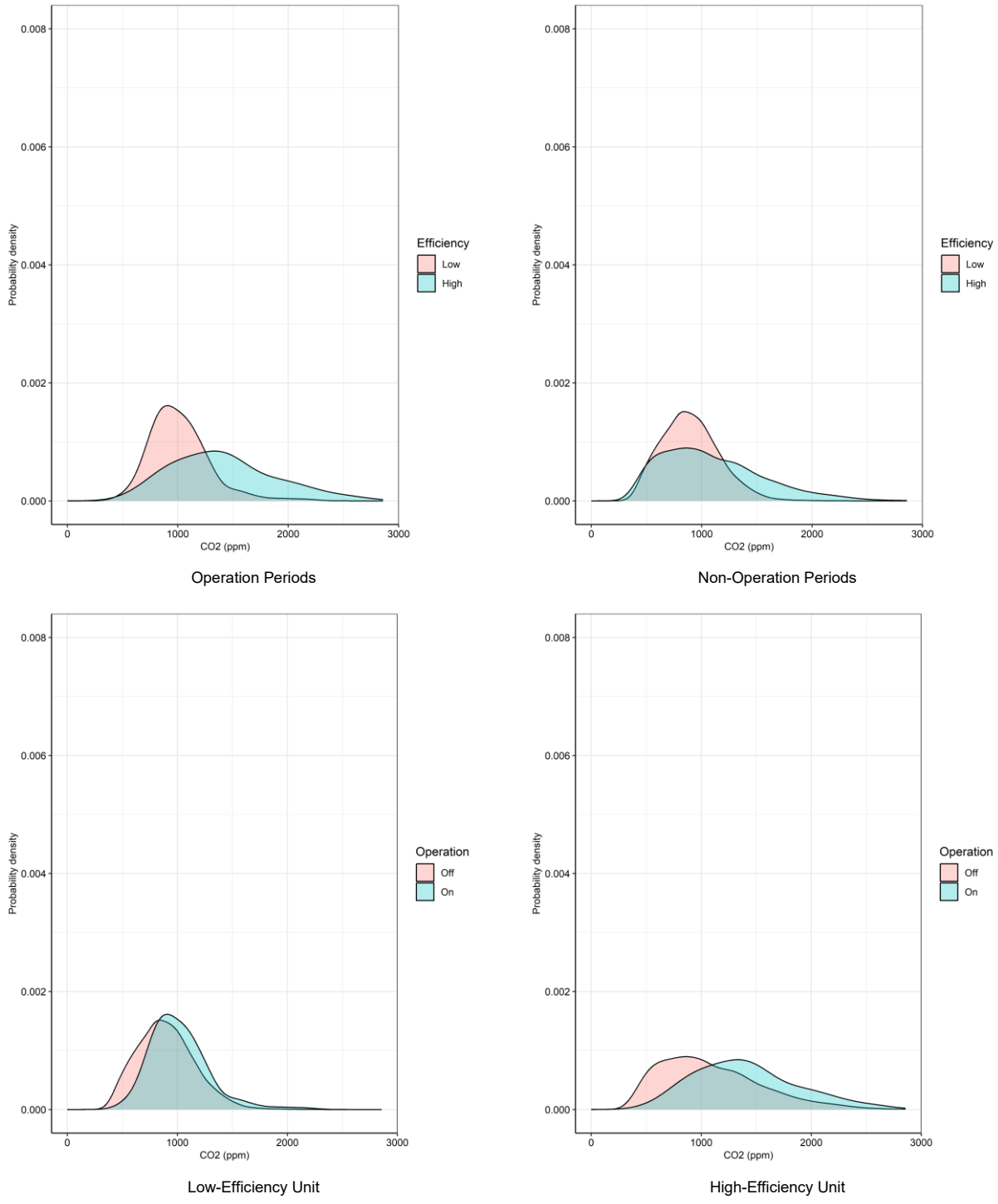

Figure C-3. DHE10 Distributions of CO_2 concentrations during operation and non-operation

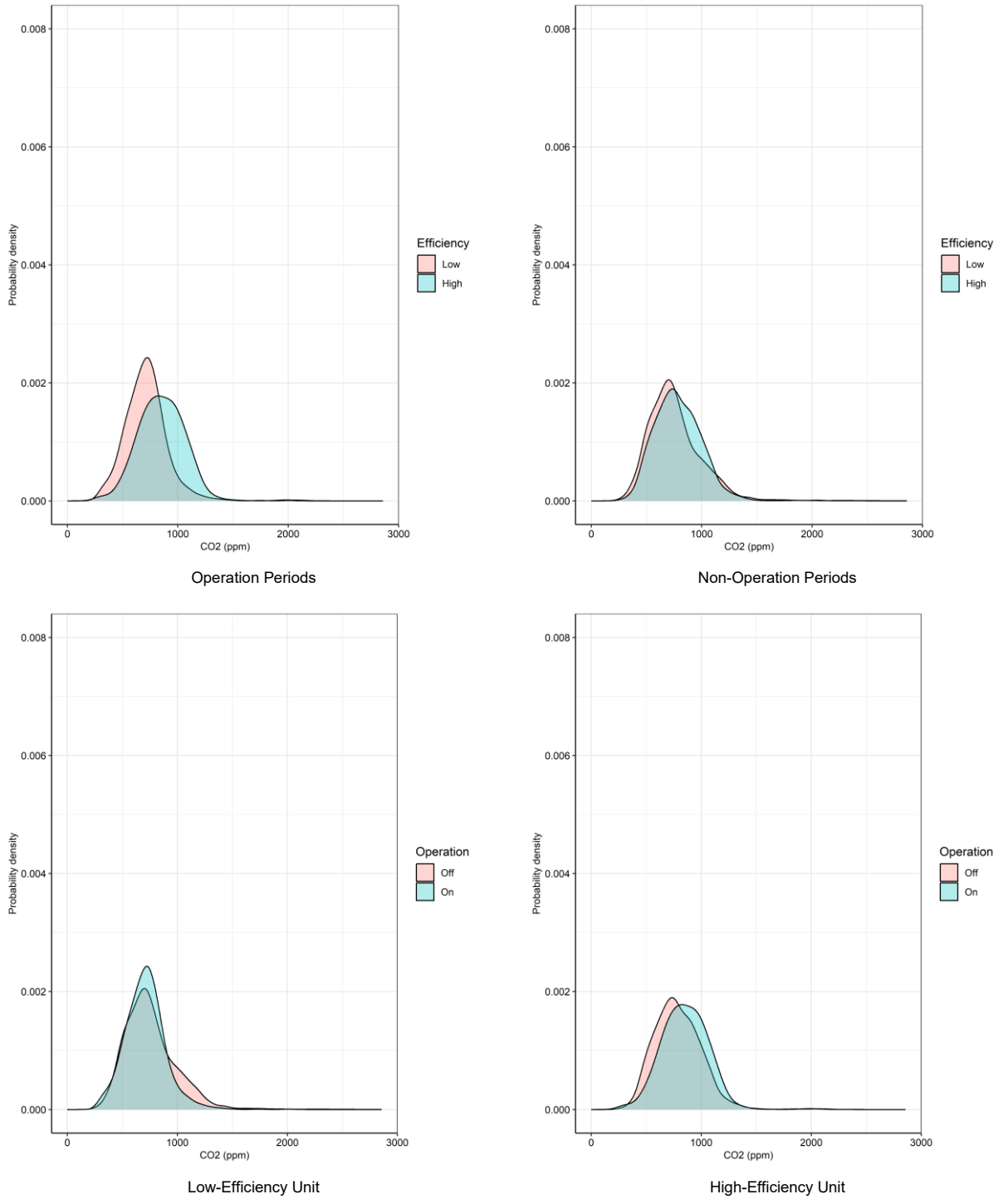

Figure C-4. DHE11 Distributions of CO_2 concentrations during operation and non-operation

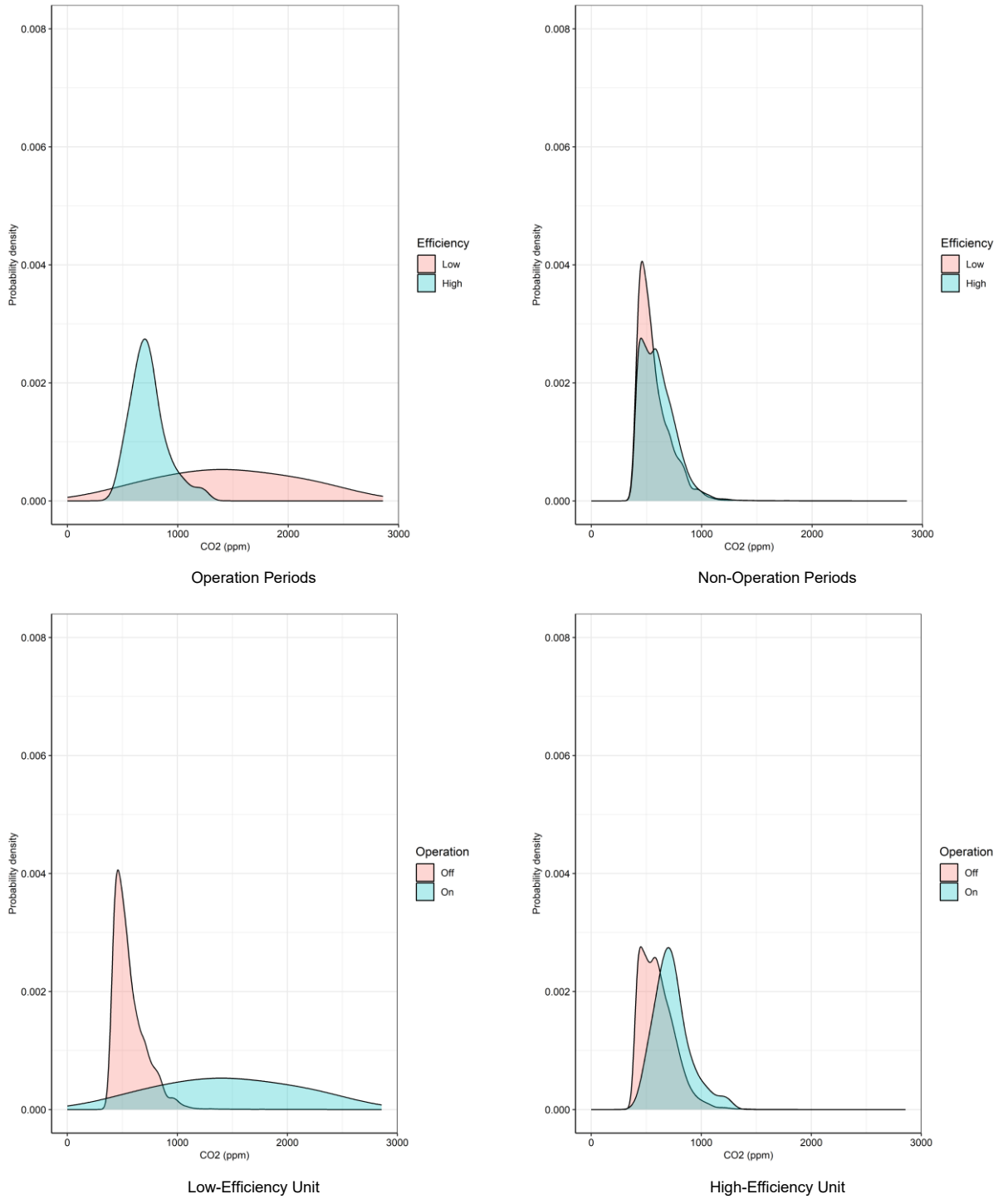

Figure C-5. DHE14 Distributions of CO_2 concentrations during operation and non-operation

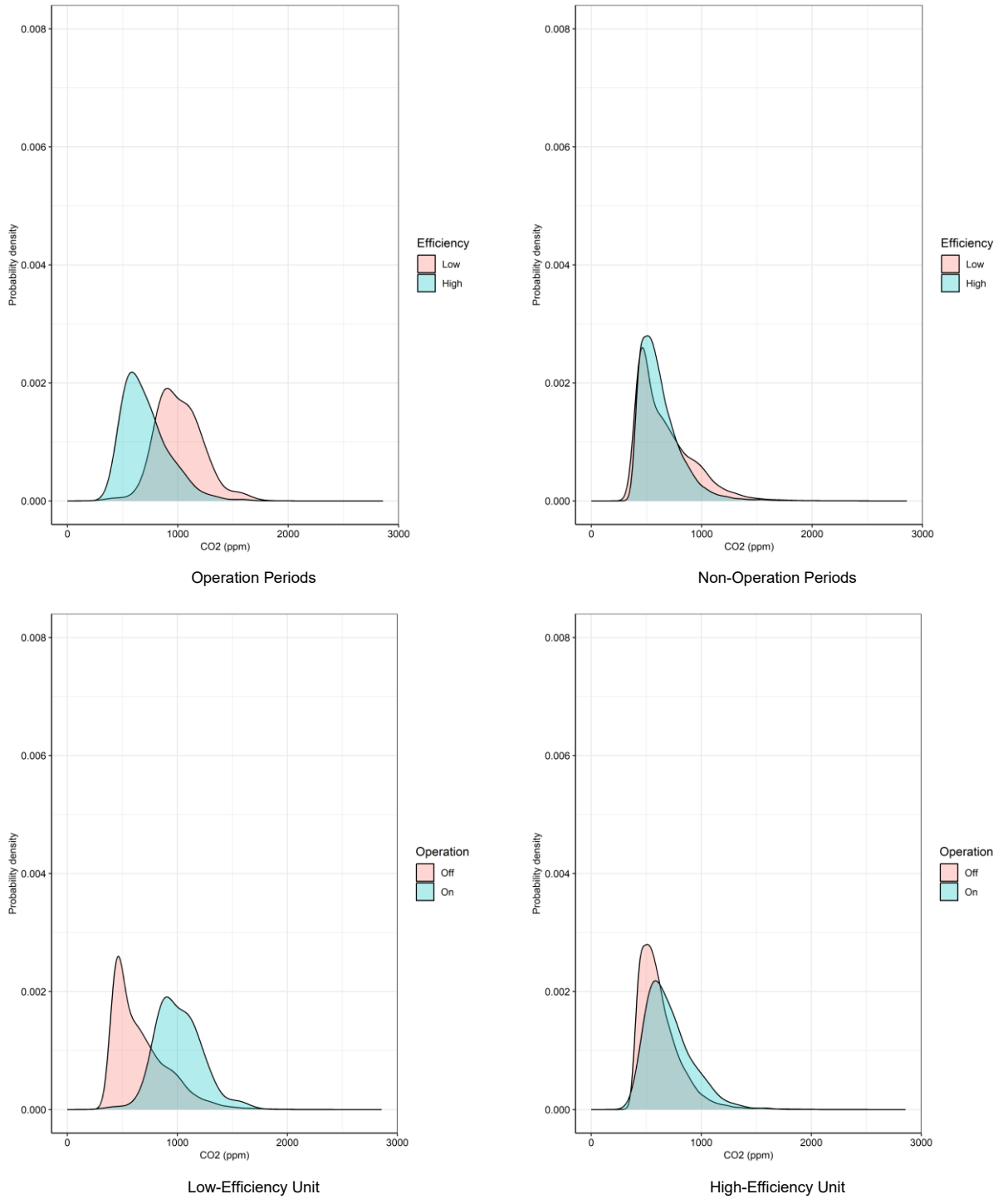

Figure C-6. DHE15 Distributions of CO_2 concentrations during operation and non-operation

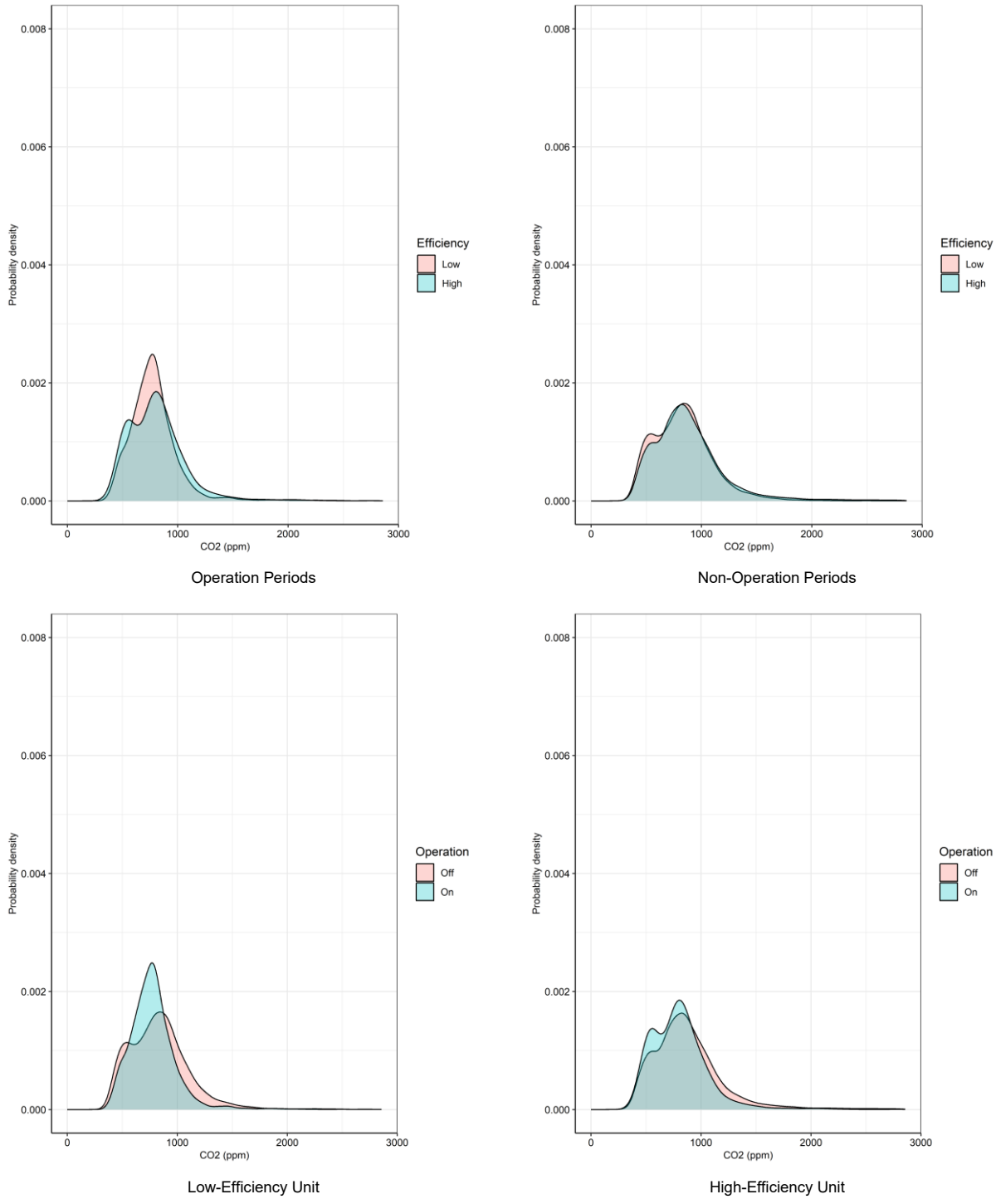

Figure C-7. DHE16 Distributions of CO_2 concentrations during operation and non-operation

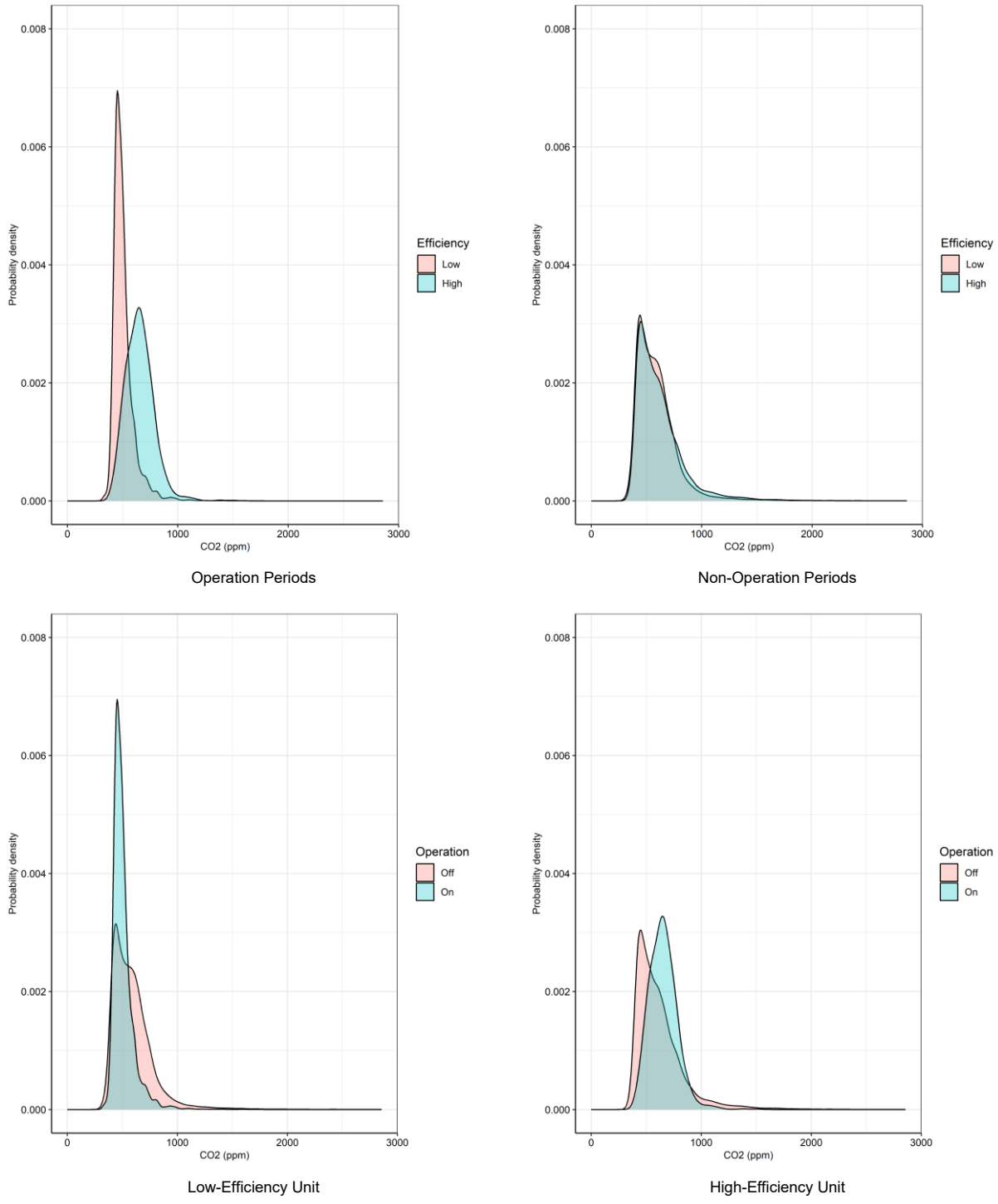

Figure C-8. DHE18 Distributions of CO_2 concentrations during operation and non-operation

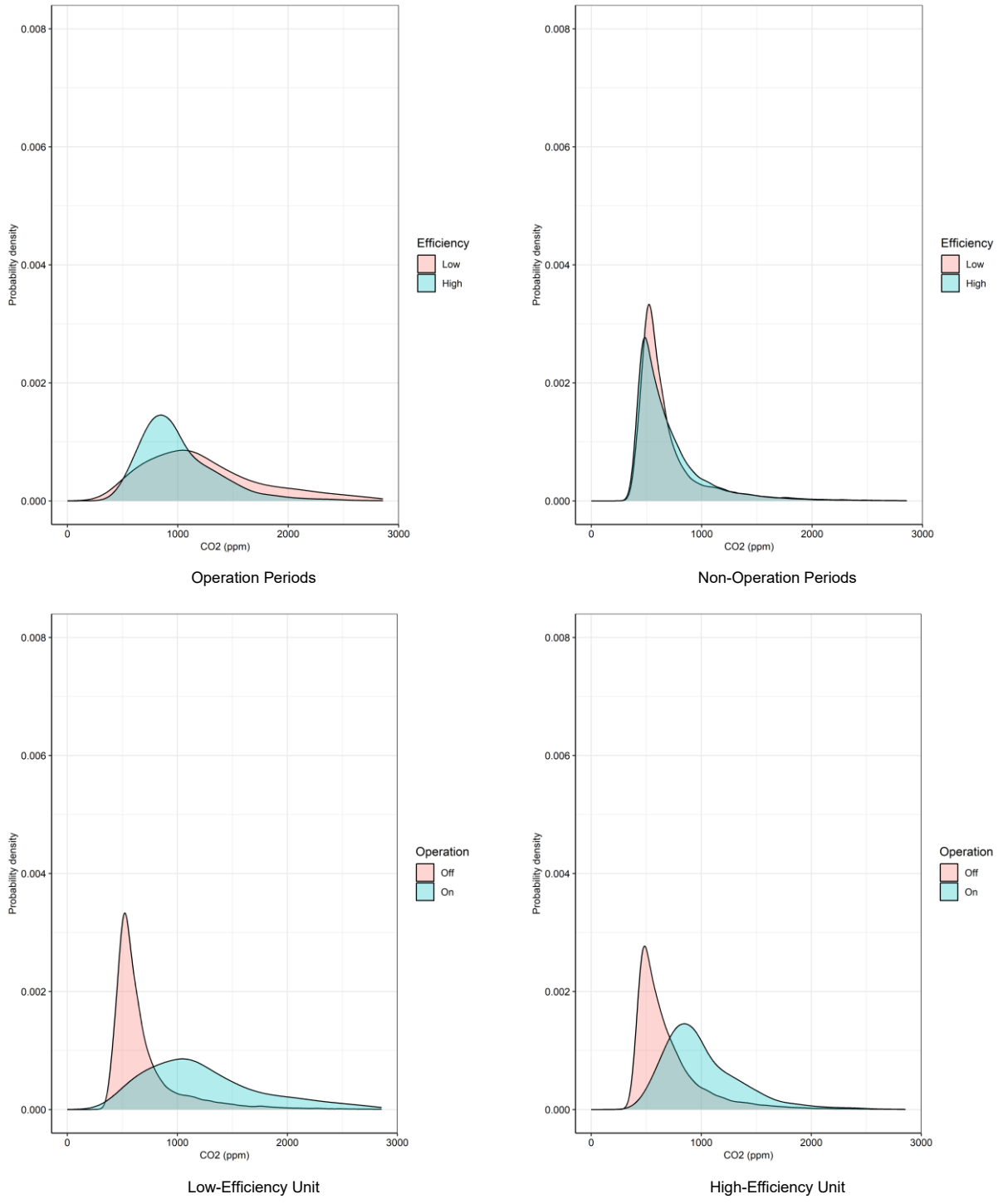

Figure C-9. DHE19 Distributions of CO_2 concentrations during operation and non-operation

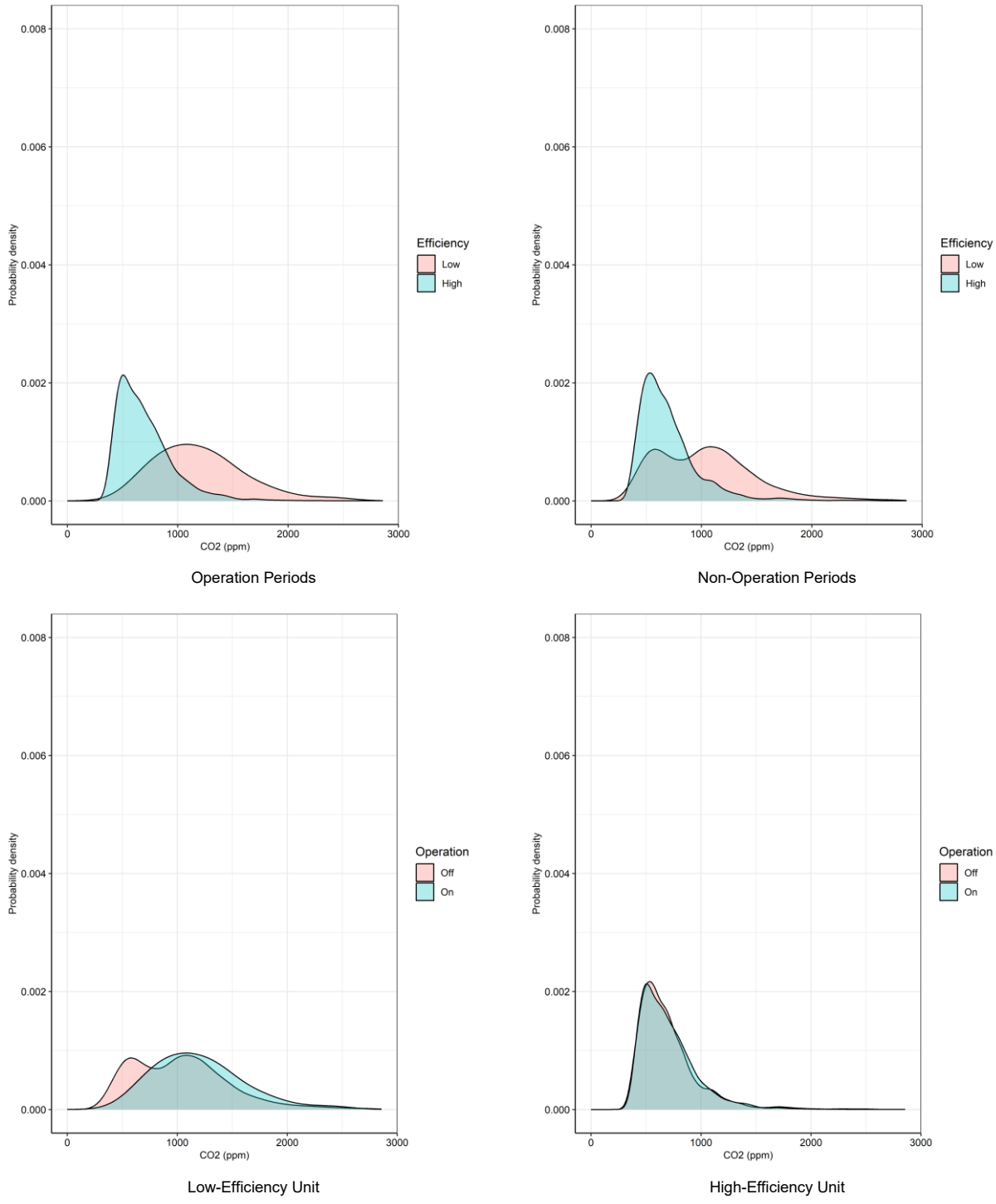

Figure C-10. DHE22 Distributions of CO_2 concentrations during operation and non-operation

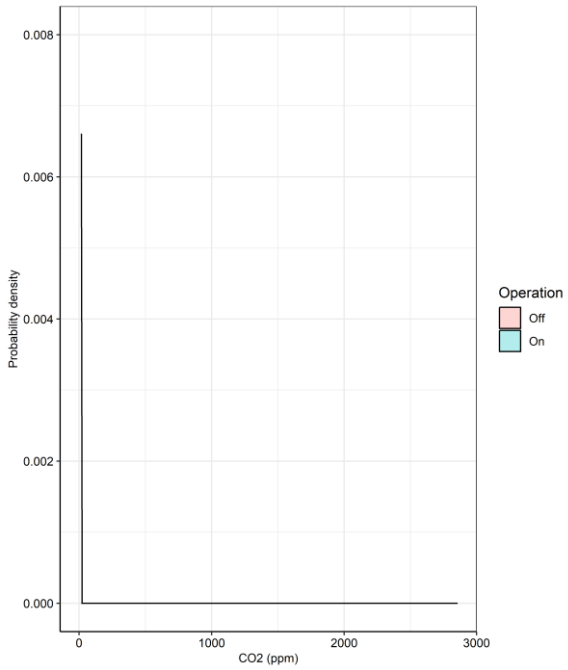

Figure C-11. DHEFF Distributions of CO_2 concentrations during operation and non-operation

Appendix D: CO Concentration in Direct-Heated Spaces During Operation and Non-Operation

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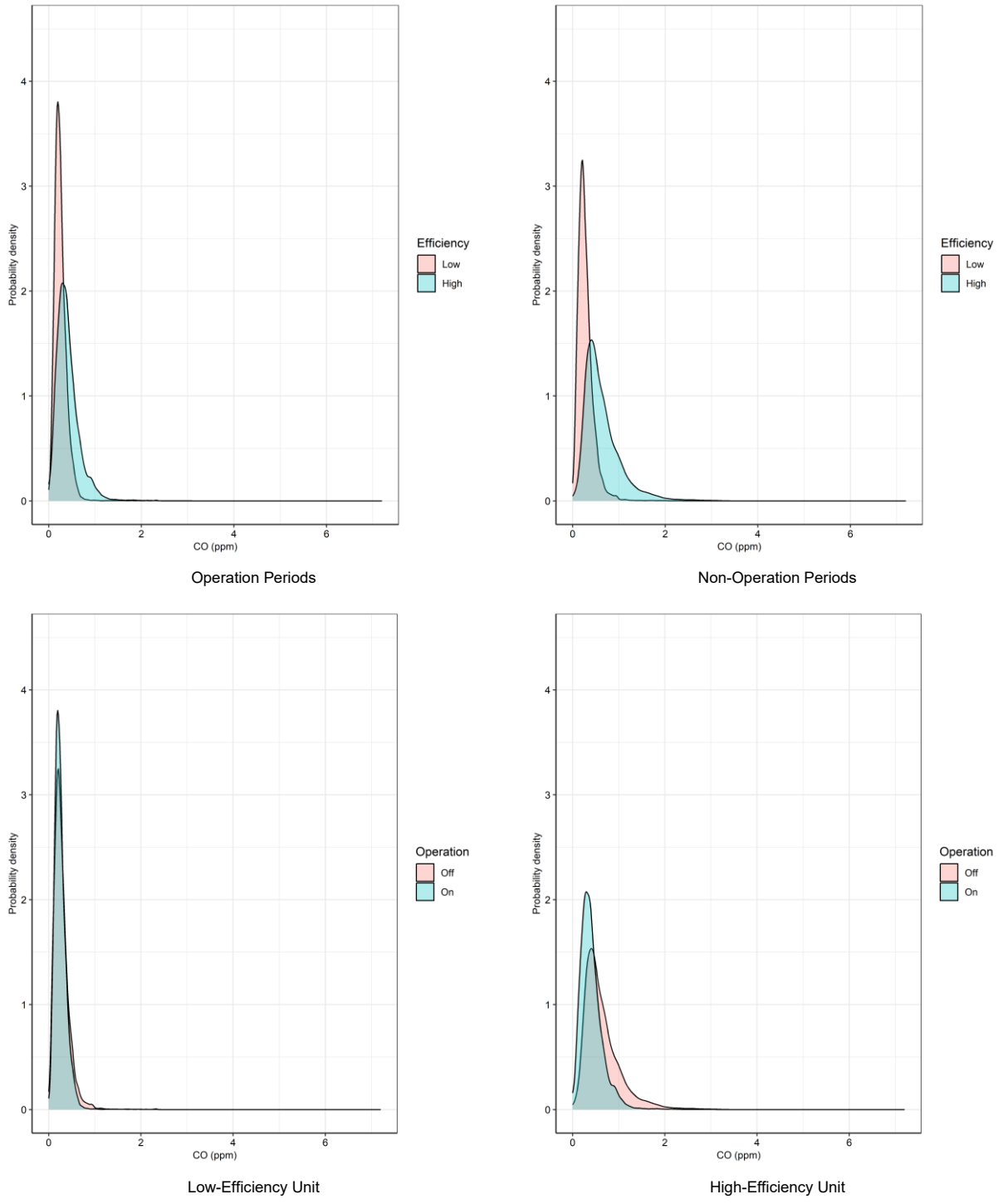


Figure D-1. DHE01 Distributions of CO concentrations during operation and non-operation

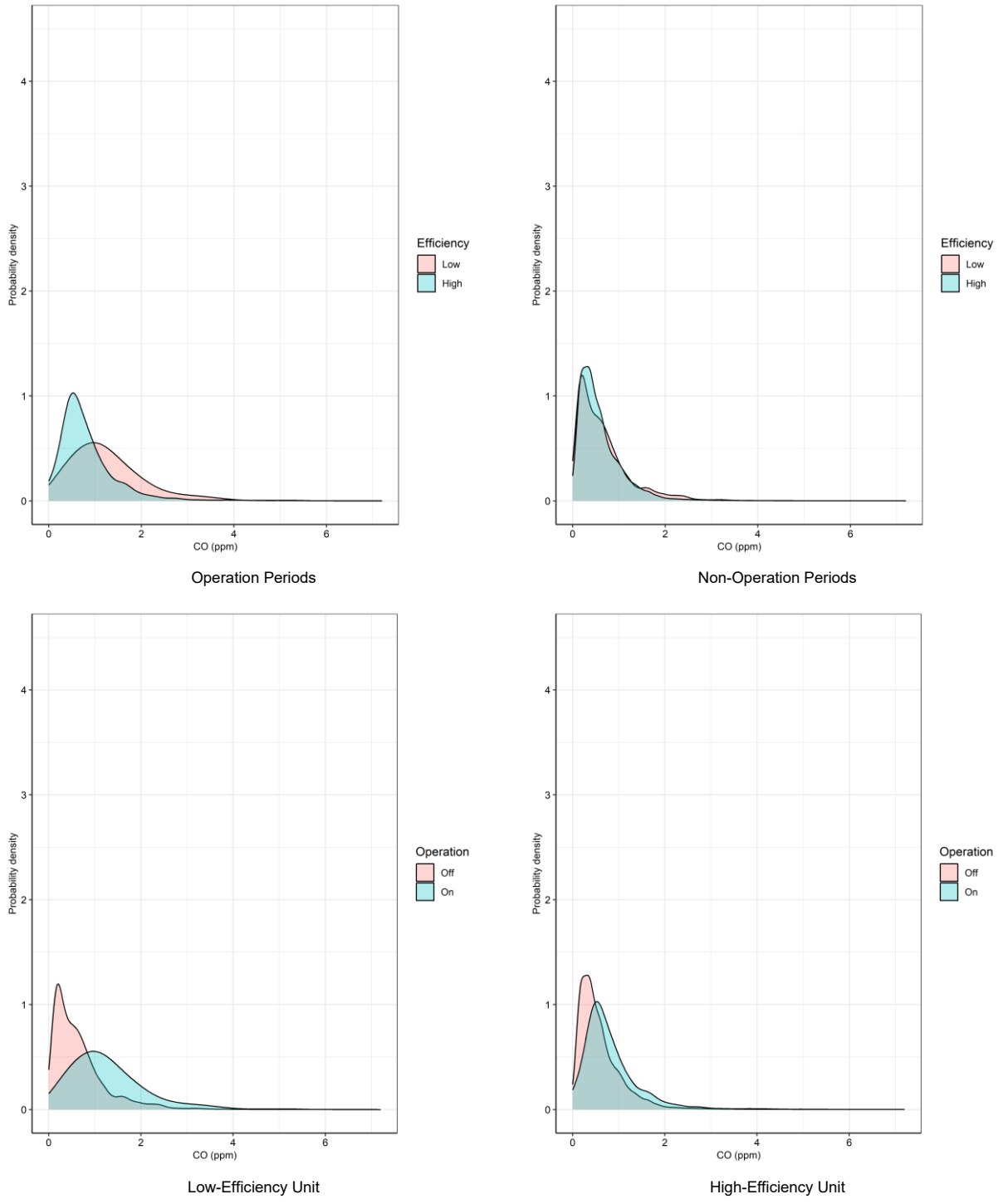


Figure D-2. DHE05 Distributions of CO concentrations during operation and non-operation

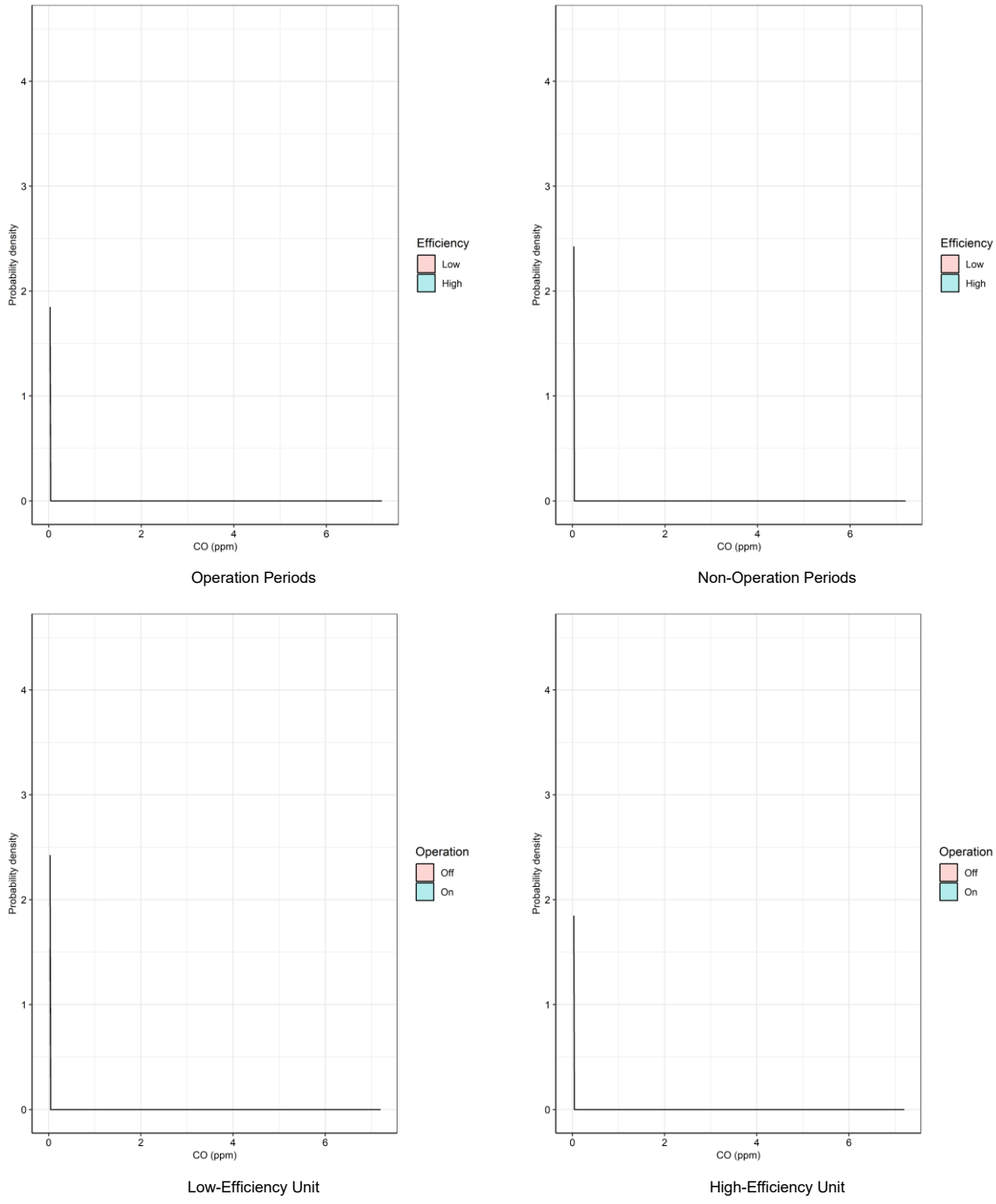


Figure D-3. DHE10 Distributions of CO concentrations during operation and non-operation

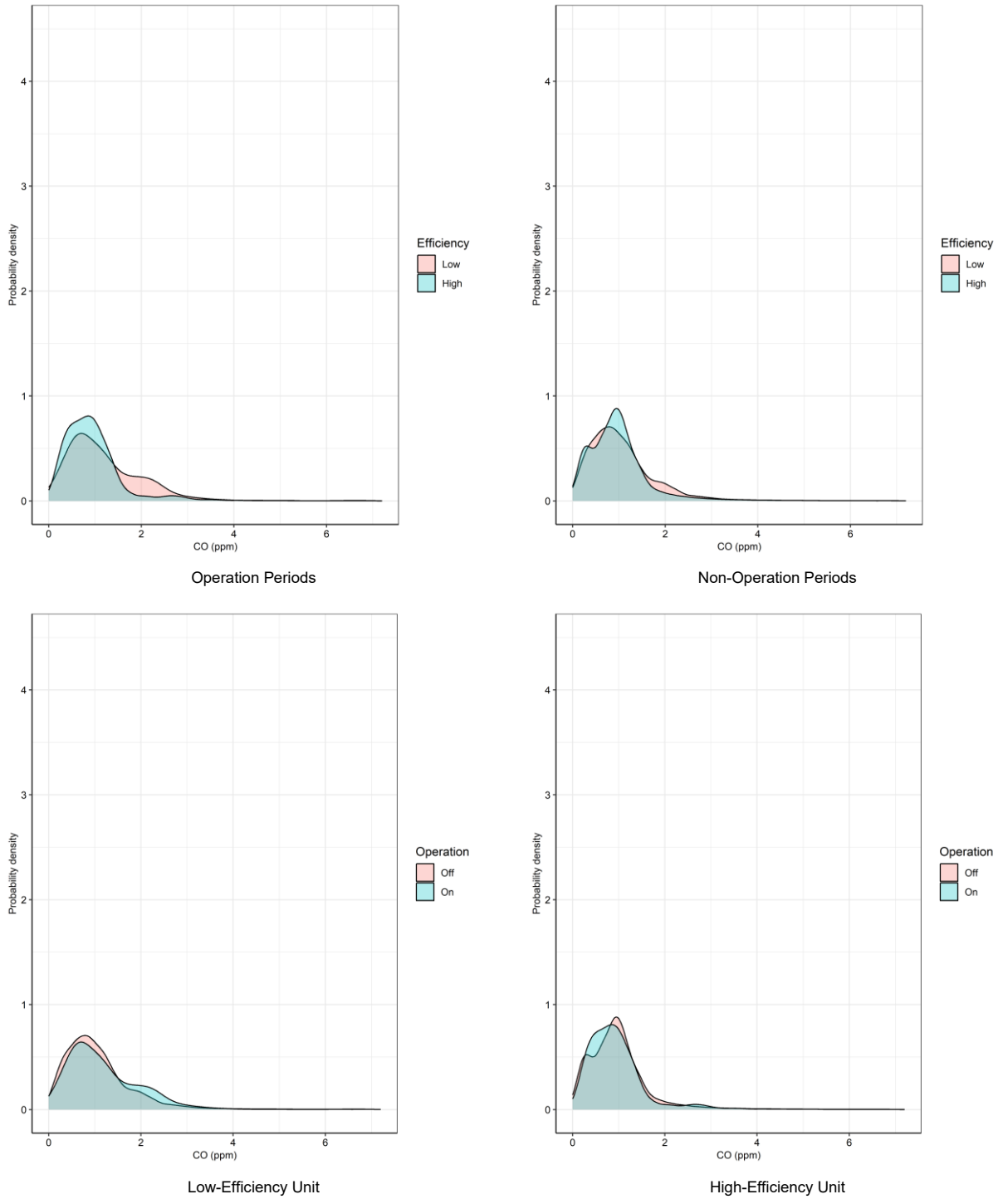


Figure D-4. DHE11 Distributions of CO concentrations during operation and non-operation

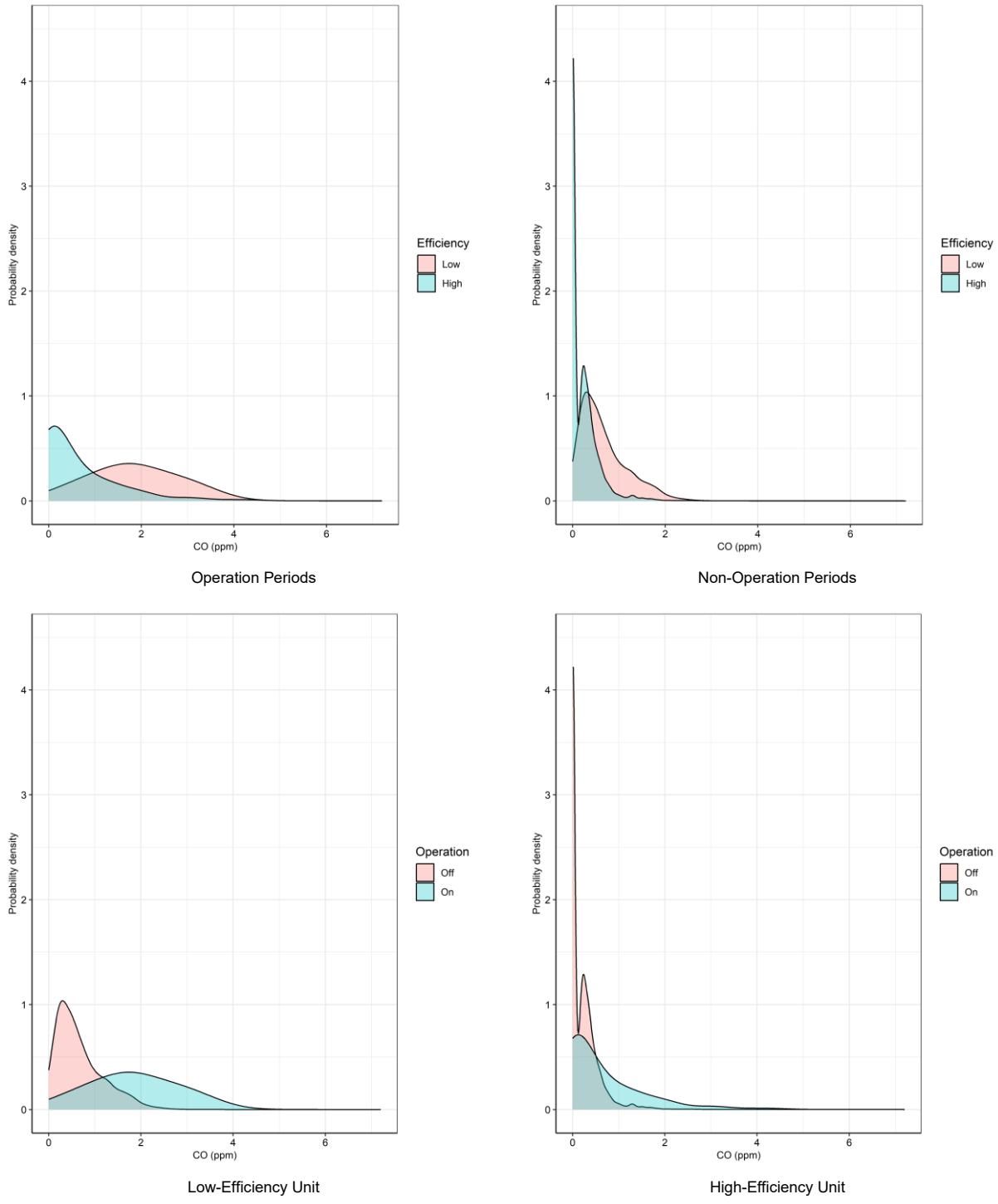


Figure D-5. DHE14 Distributions of CO concentrations during operation and non-operation

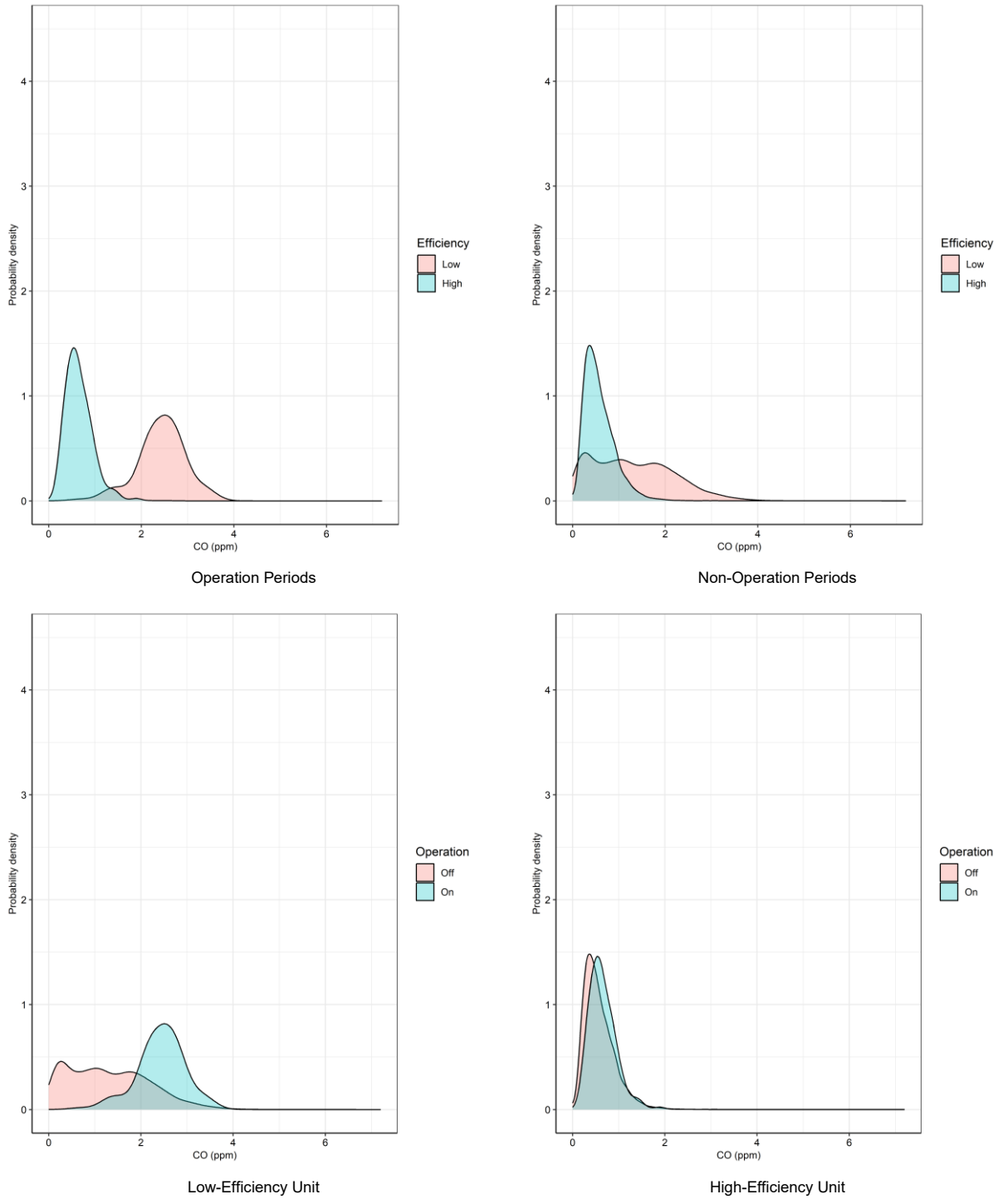


Figure D-6. DHE15 Distributions of CO concentrations during operation and non-operation

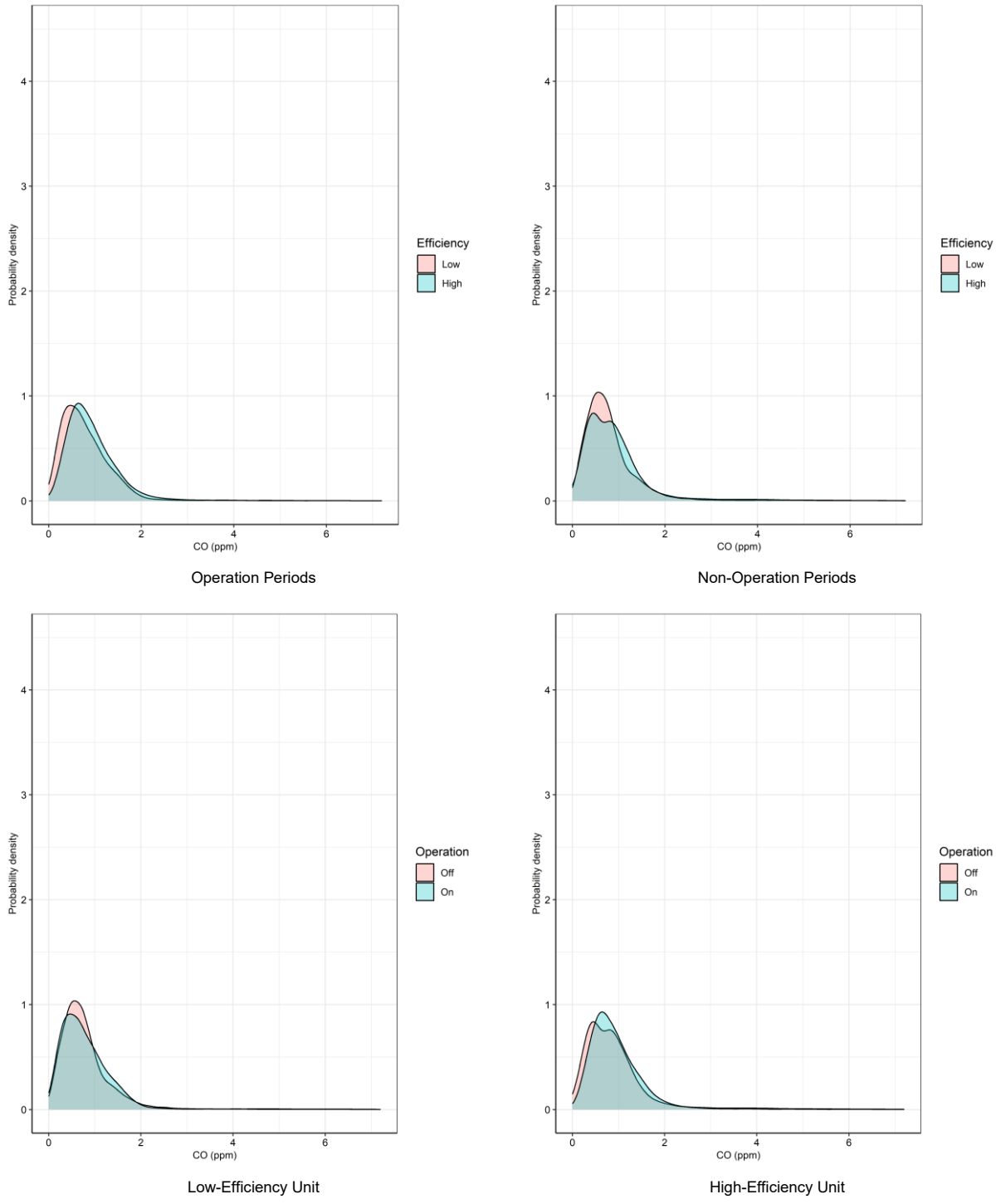


Figure D-7. DHE16 Distributions of CO concentrations during operation and non-operation

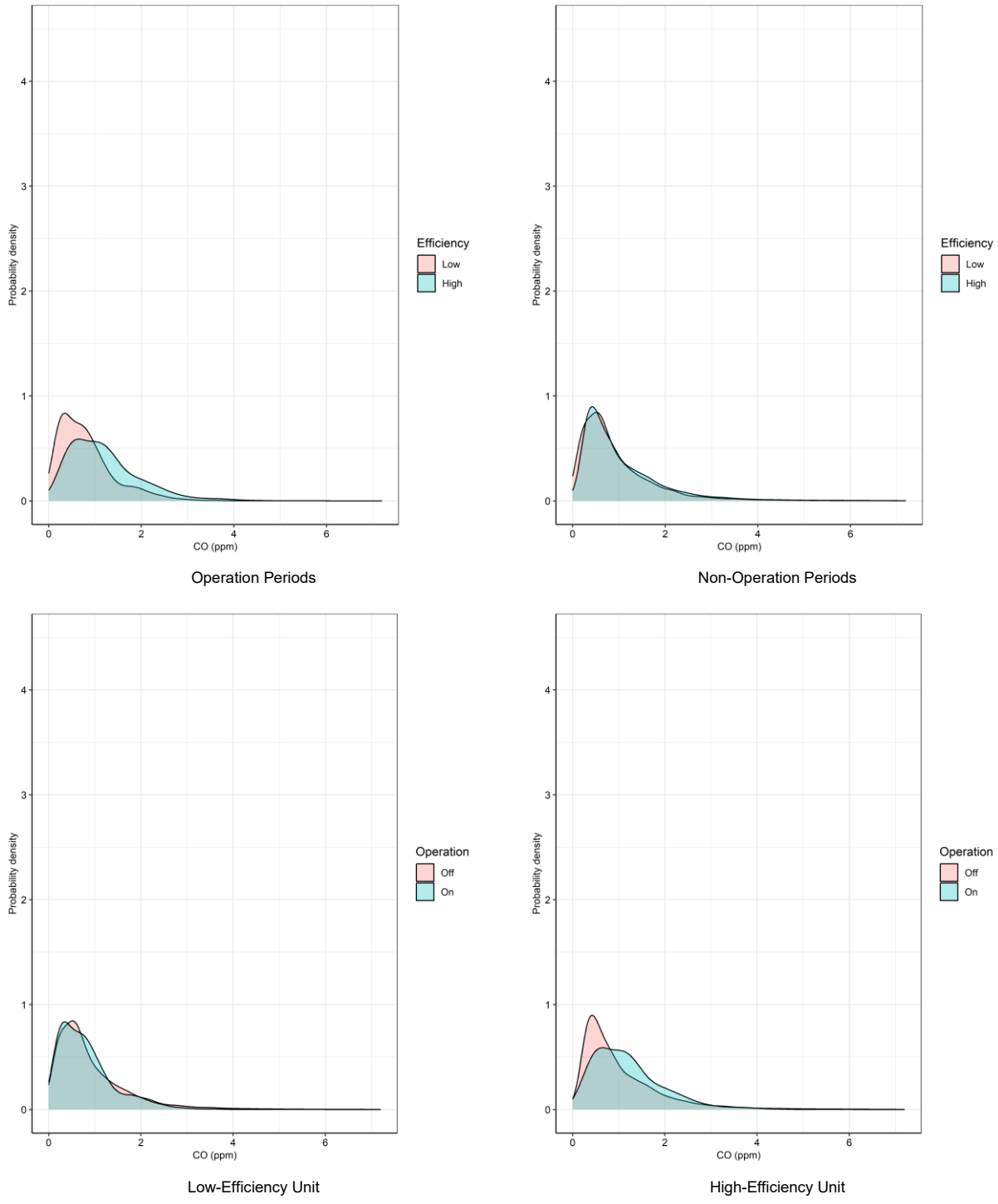


Figure D-8. DHE18 Distributions of CO concentrations during operation and non-operation

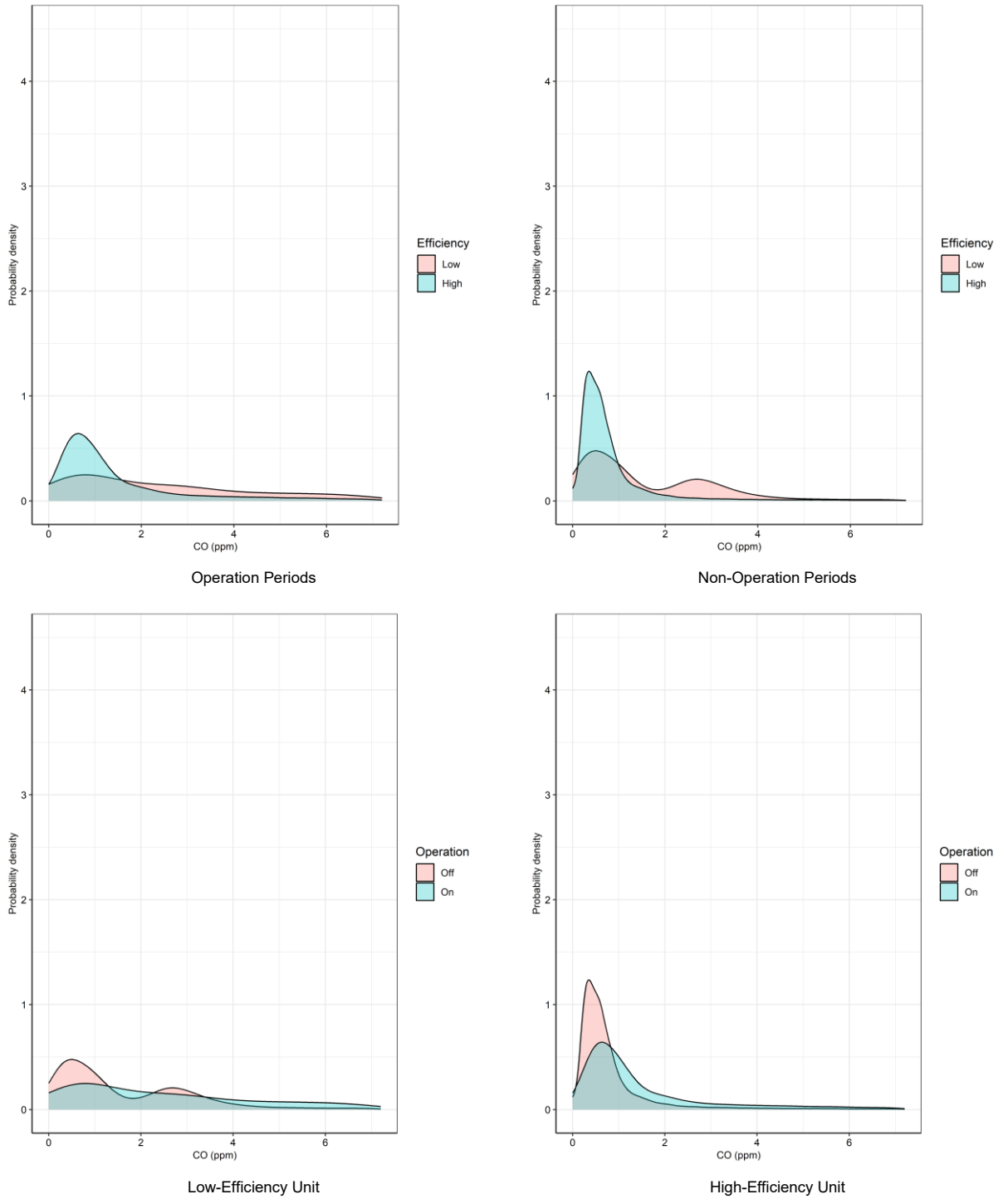


Figure D-9. DHE19 Distributions of CO concentrations during operation and non-operation

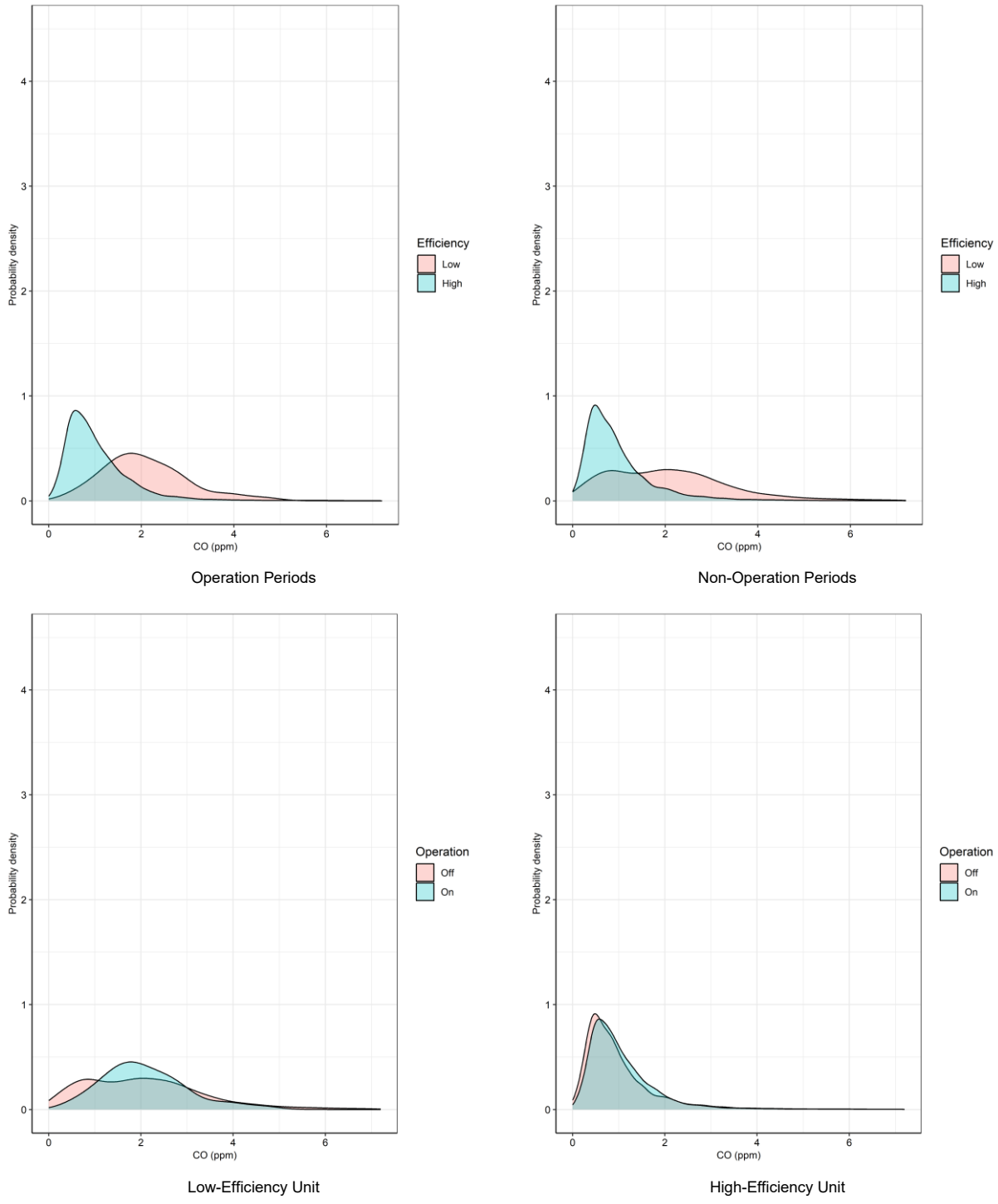
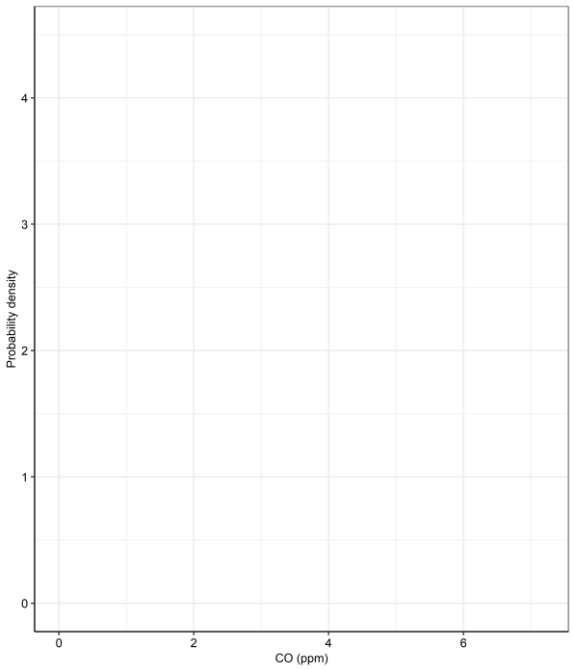


Figure D-10. DHE22 Distributions of CO concentrations during operation and non-operation



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Appendix E: $PM_{2.5}$ Concentration in Direct-Heated Spaces During Operation and Non-Operation

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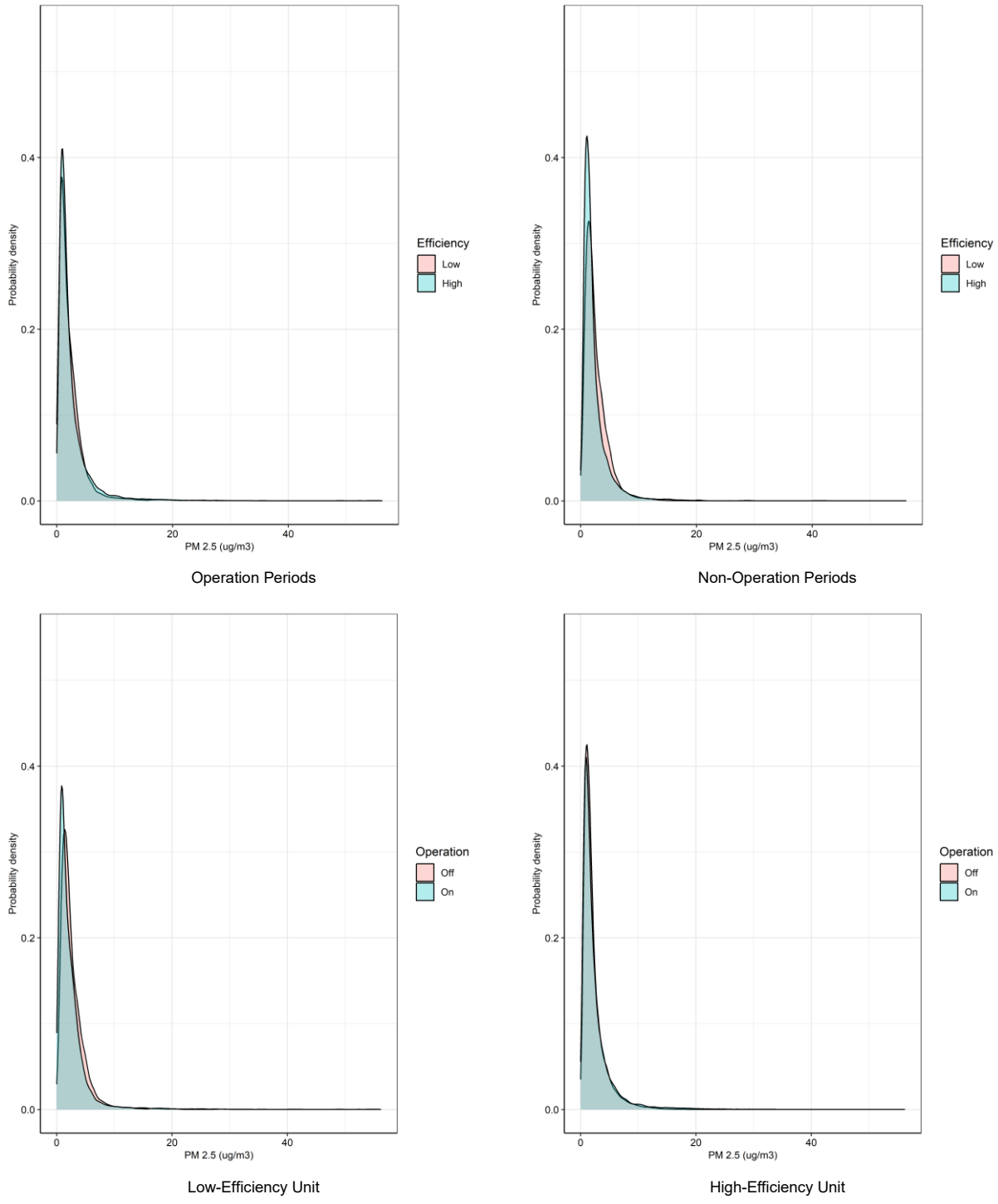

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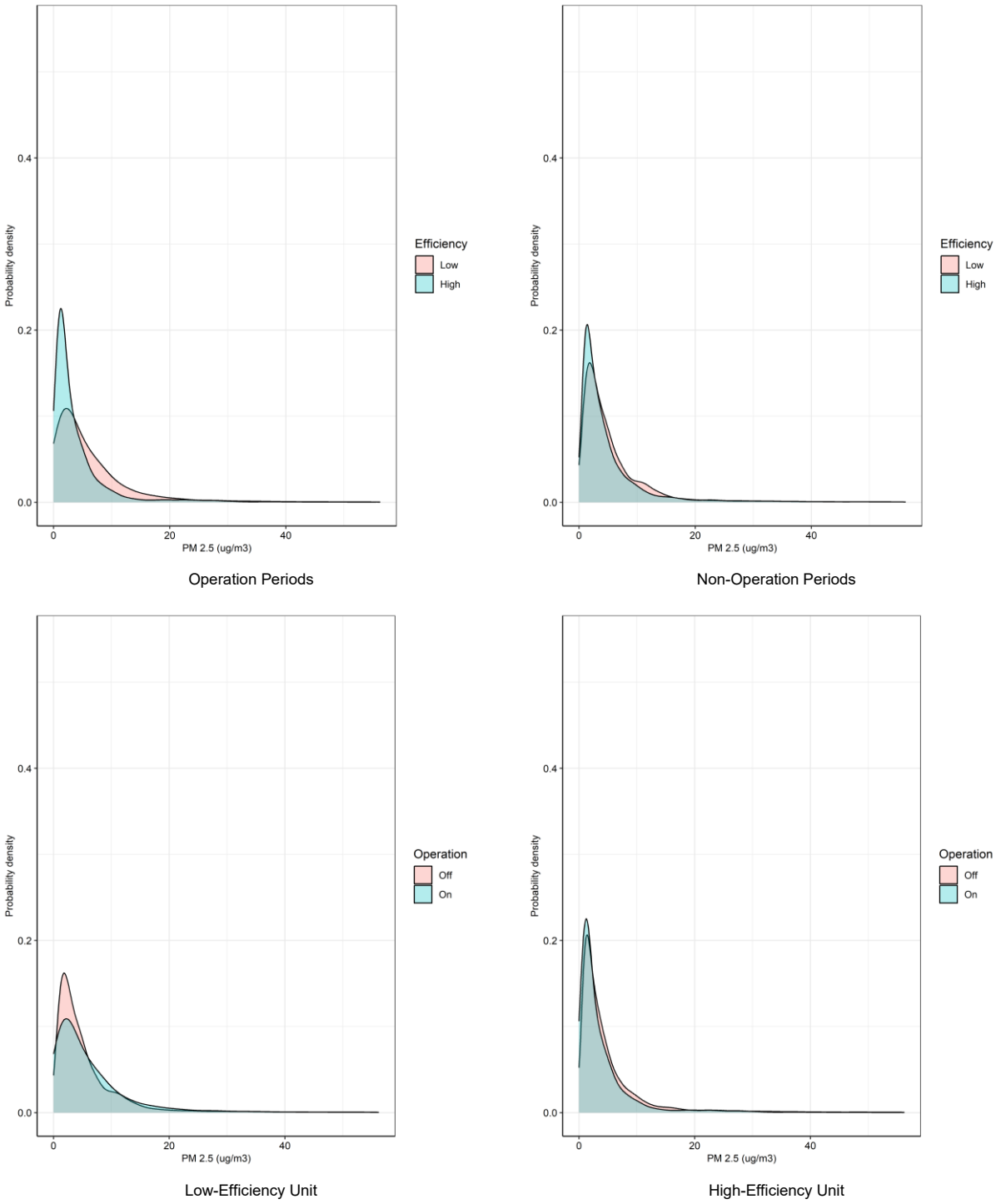

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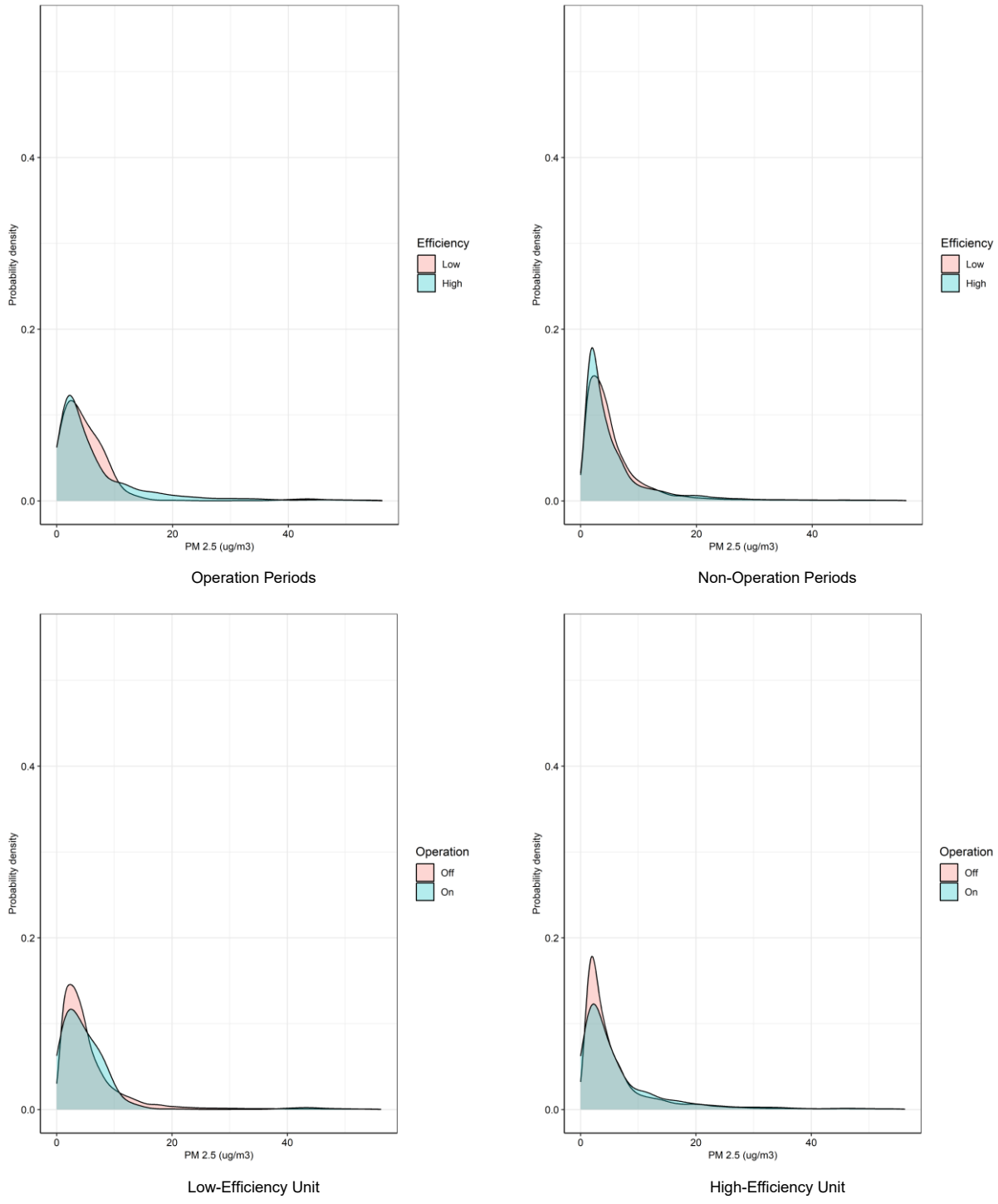


Figure E-3. DHE10 Distributions of $PM_{2.5}$ concentrations during operation and non-operation

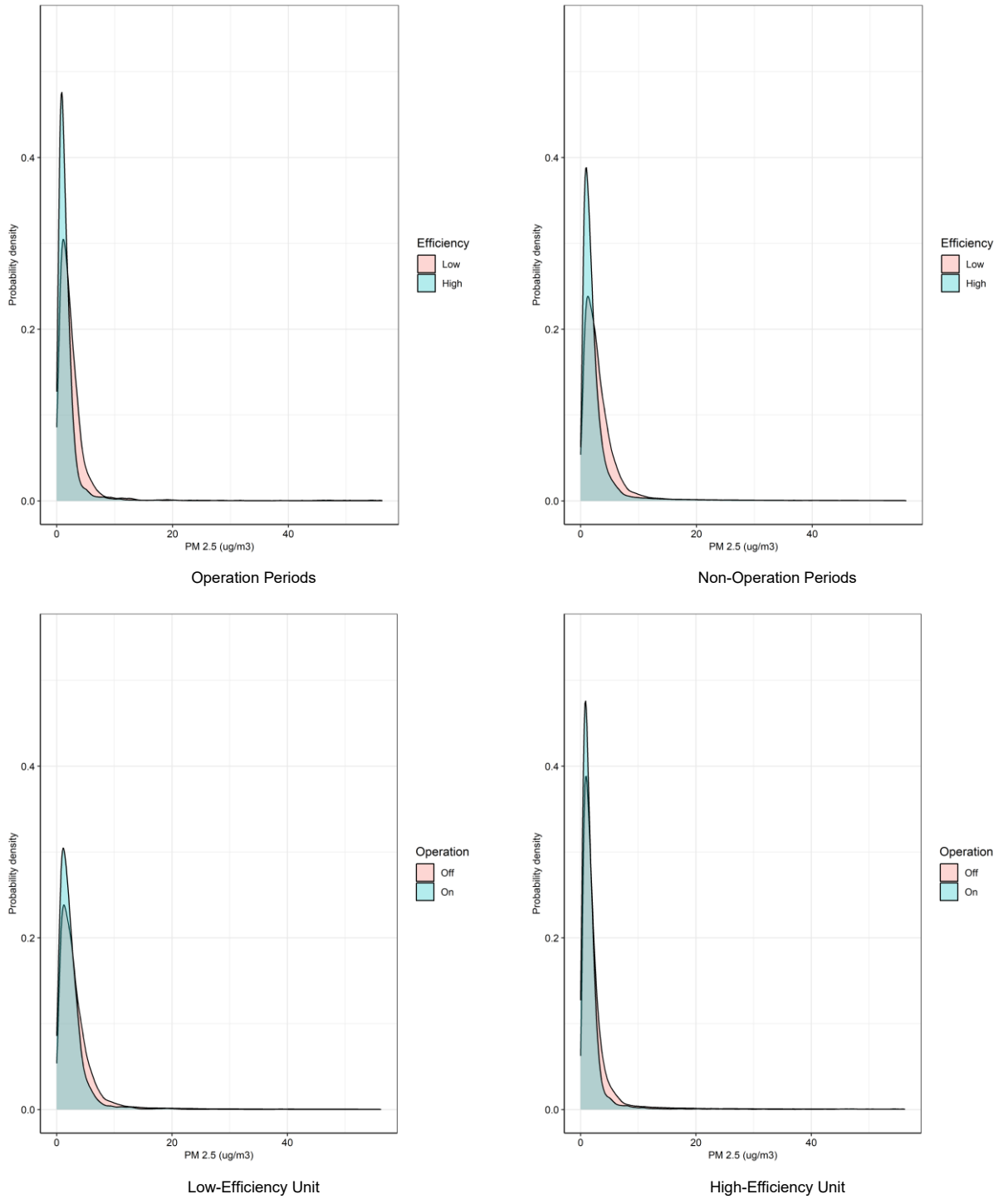


Figure E-4. DHE11 Distributions of $PM_{2.5}$ concentrations during operation and non-operation

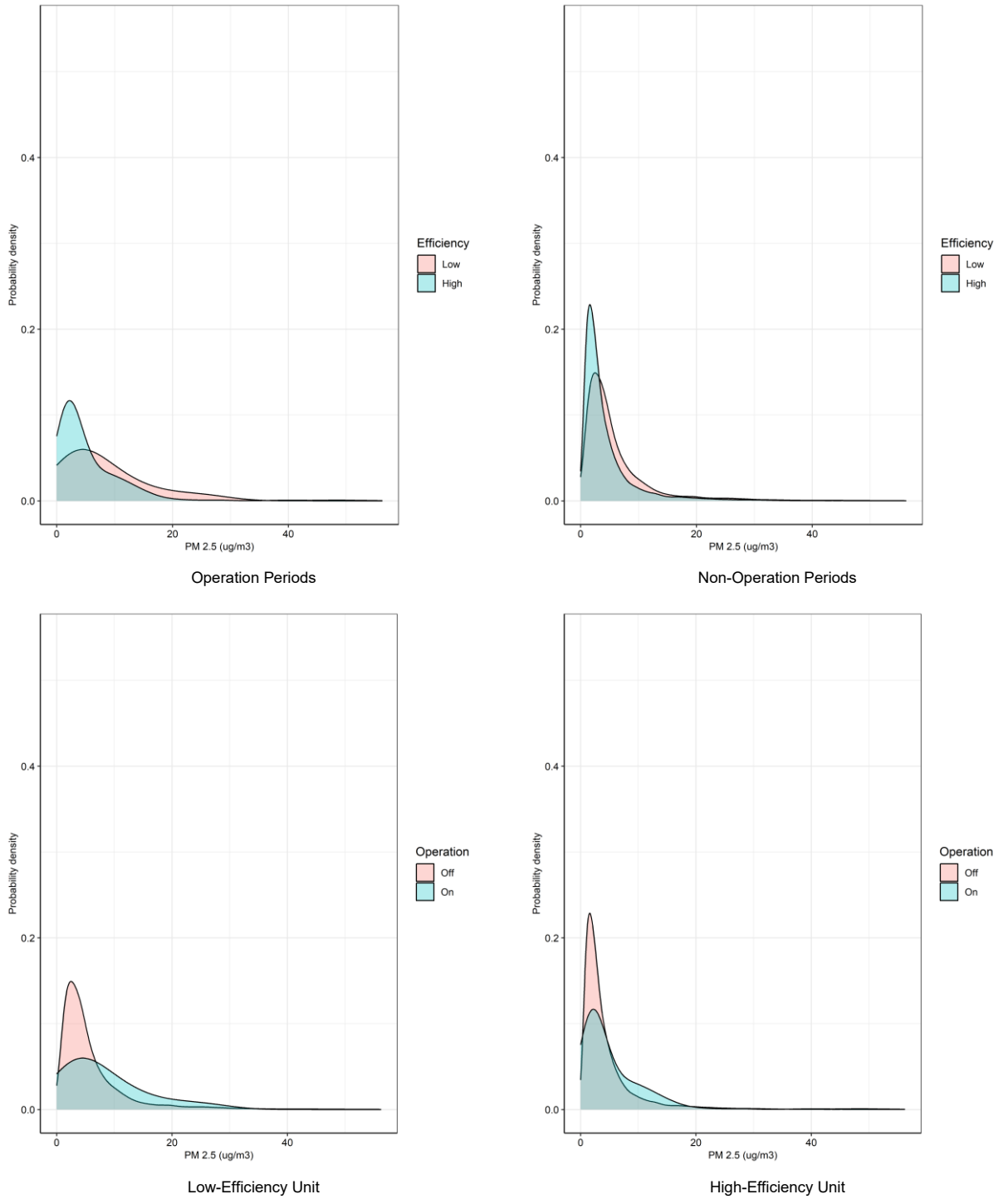


Figure E-5. DHE14 Distributions of $PM_{2.5}$ concentrations during operation and non-operation

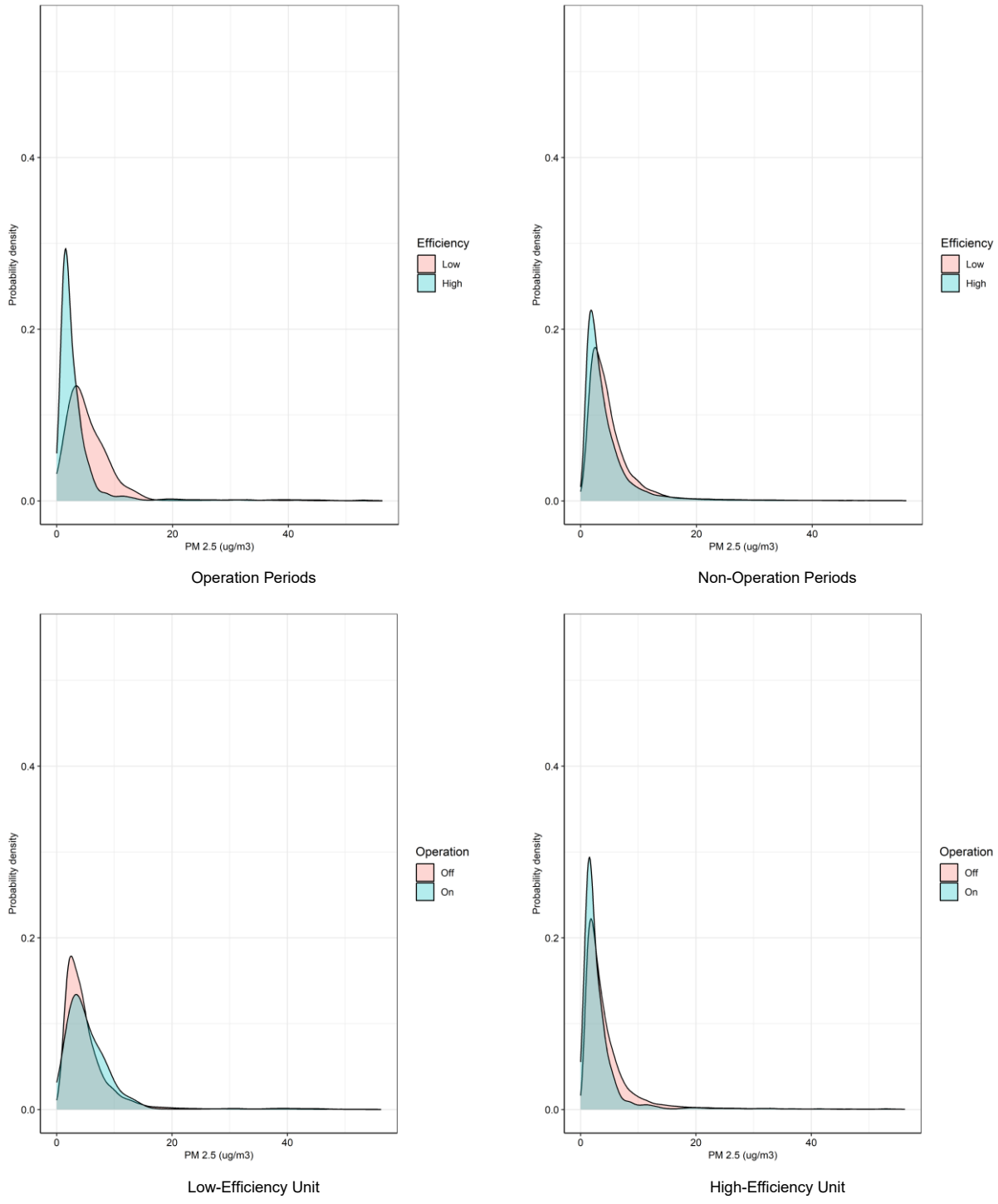


Figure E-6. DHE15 Distributions of $PM_{2.5}$ concentrations during operation and non-operation

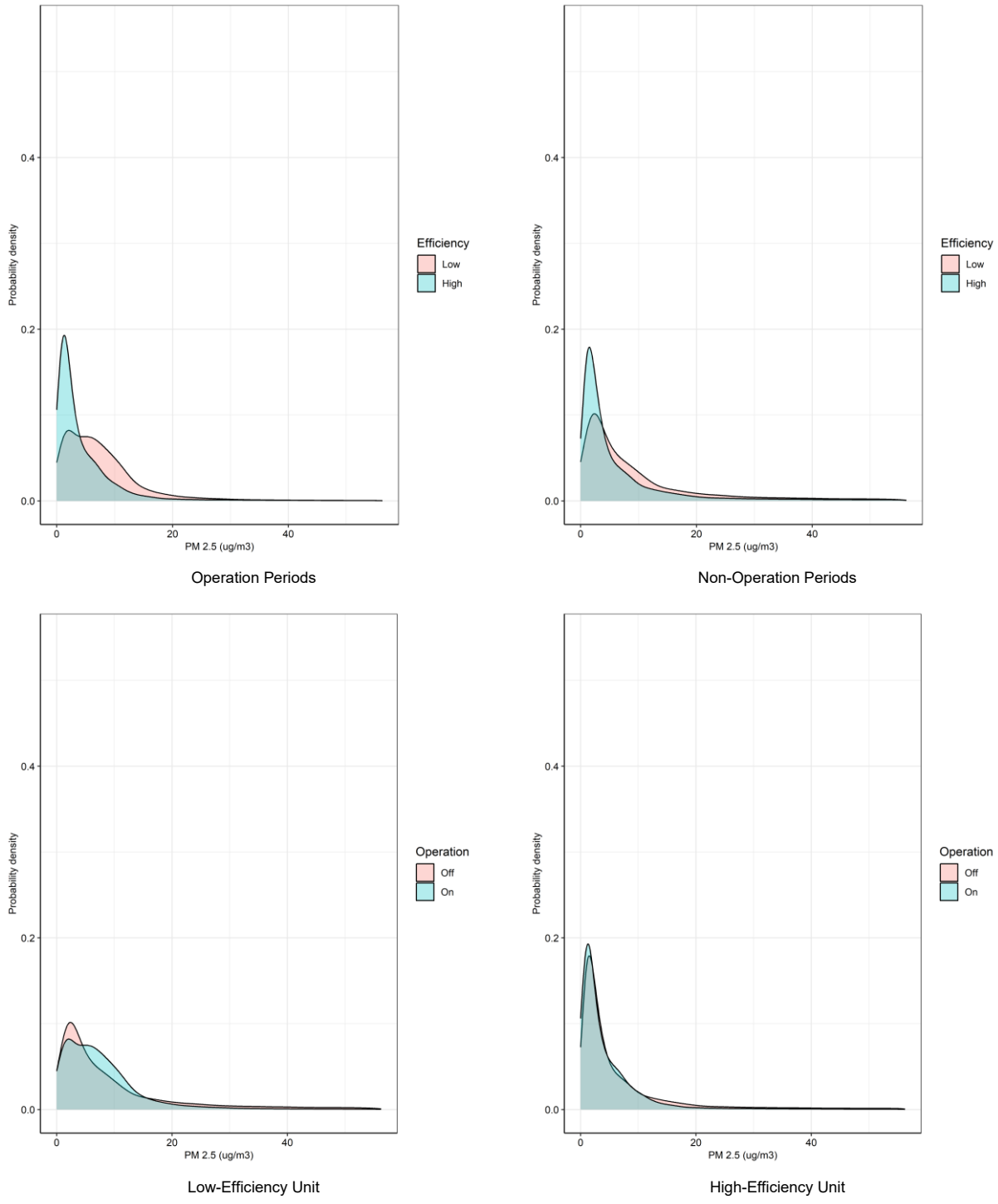


Figure E-7. DHE16 Distributions of $PM_{2.5}$ concentrations during operation and non-operation

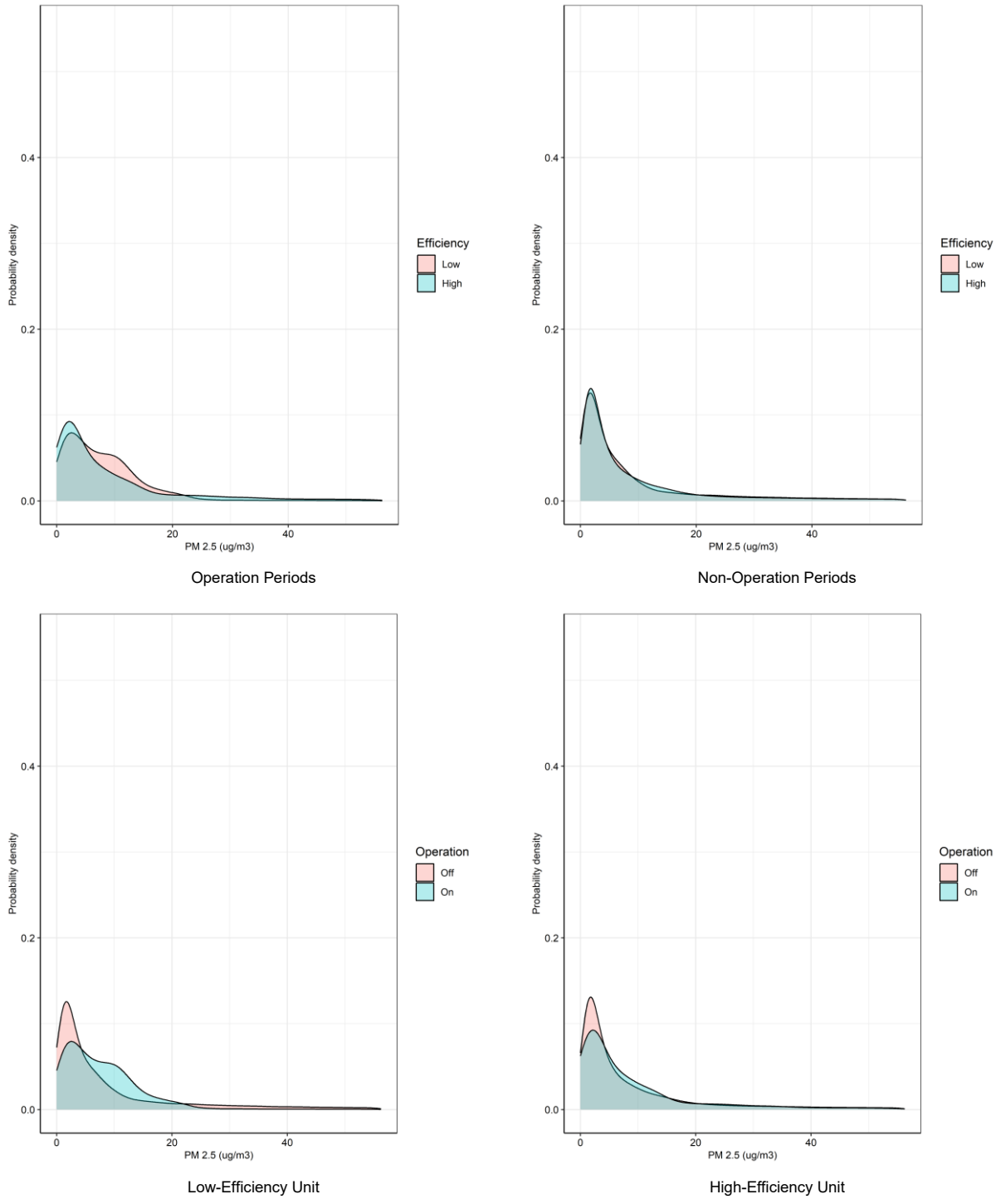


Figure E-8. DHE18 Distributions of $PM_{2.5}$ concentrations during operation and non-operation

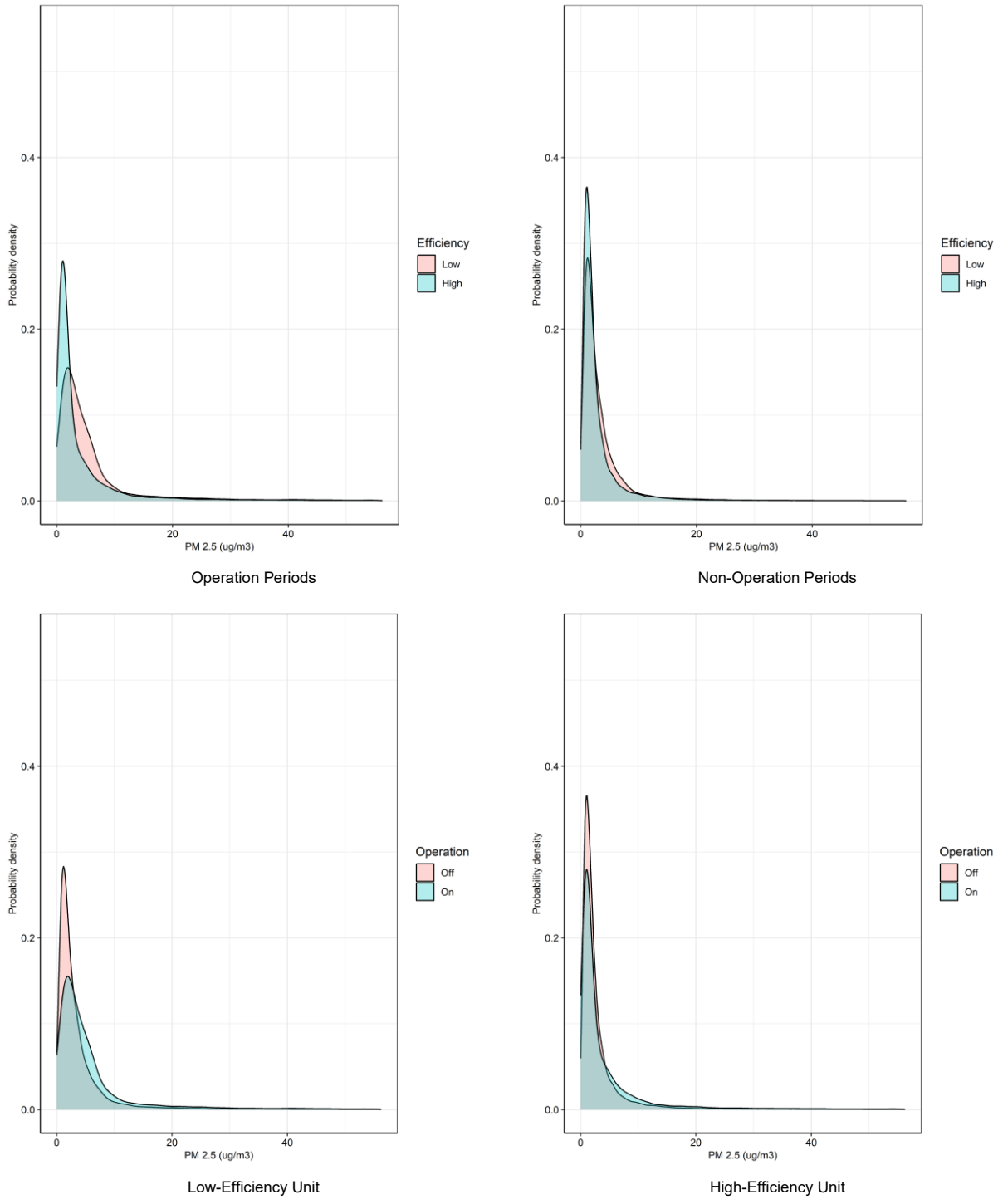


Figure E-9. DHE19 Distributions of $PM_{2.5}$ concentrations during operation and non-operation

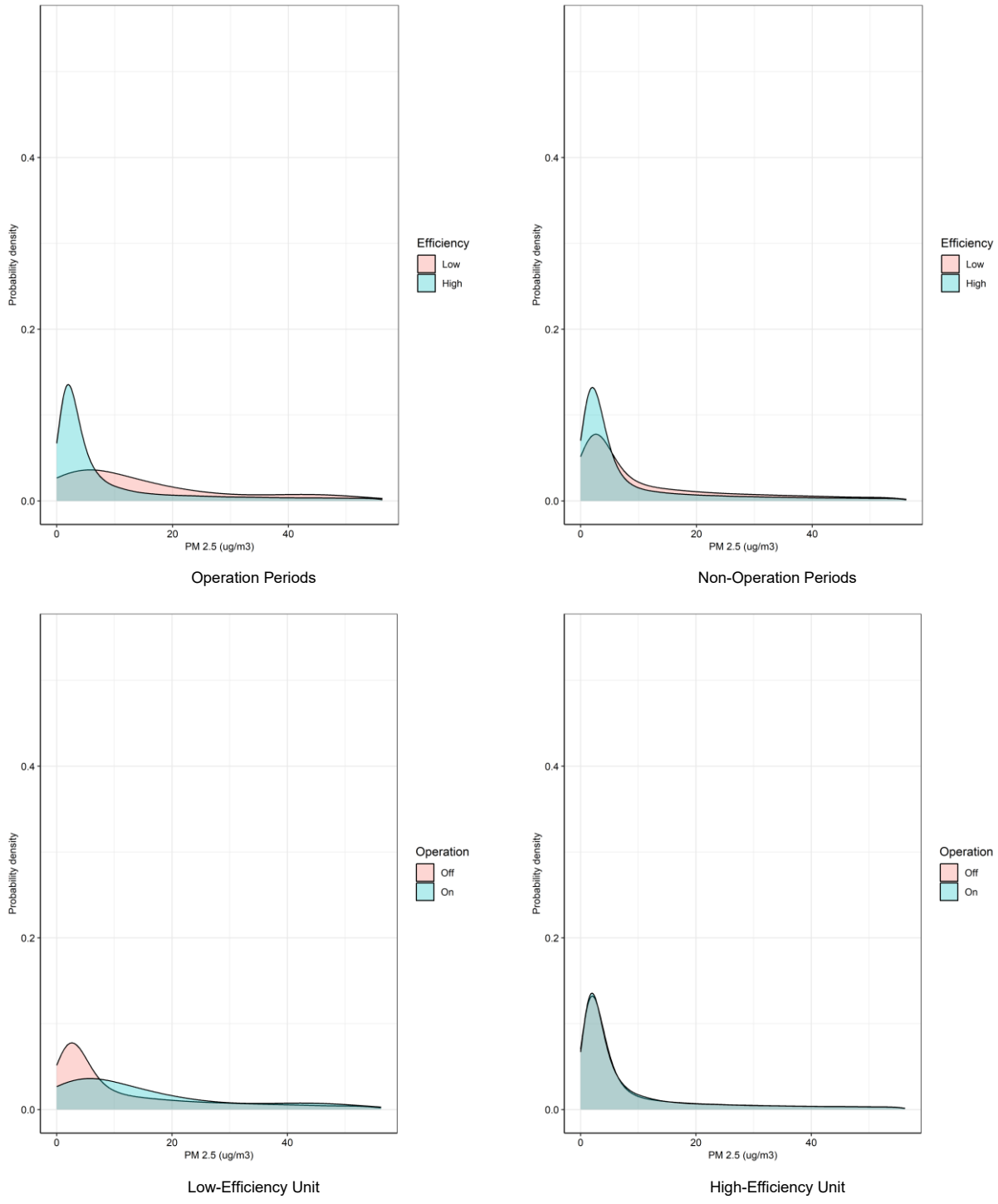
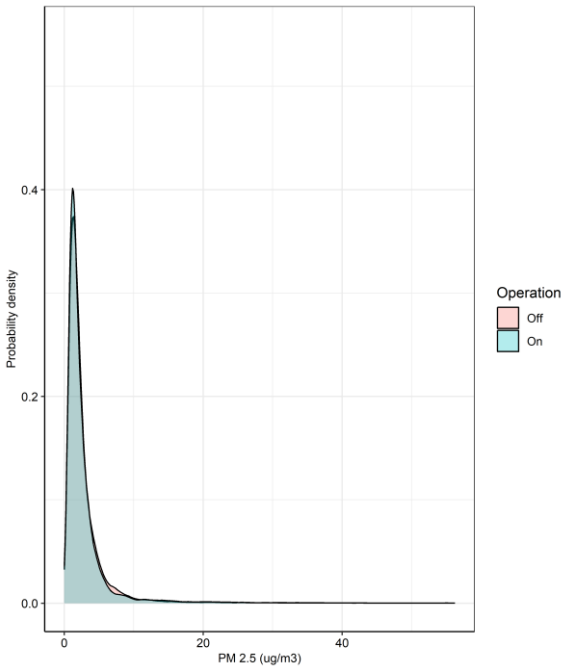


Figure E-10. DHE22 Distributions of $PM_{2.5}$ concentrations during operation and non-operation



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Appendix F: PM_{10} Concentration in Direct-Heated Spaces During Operation and Non-Operation

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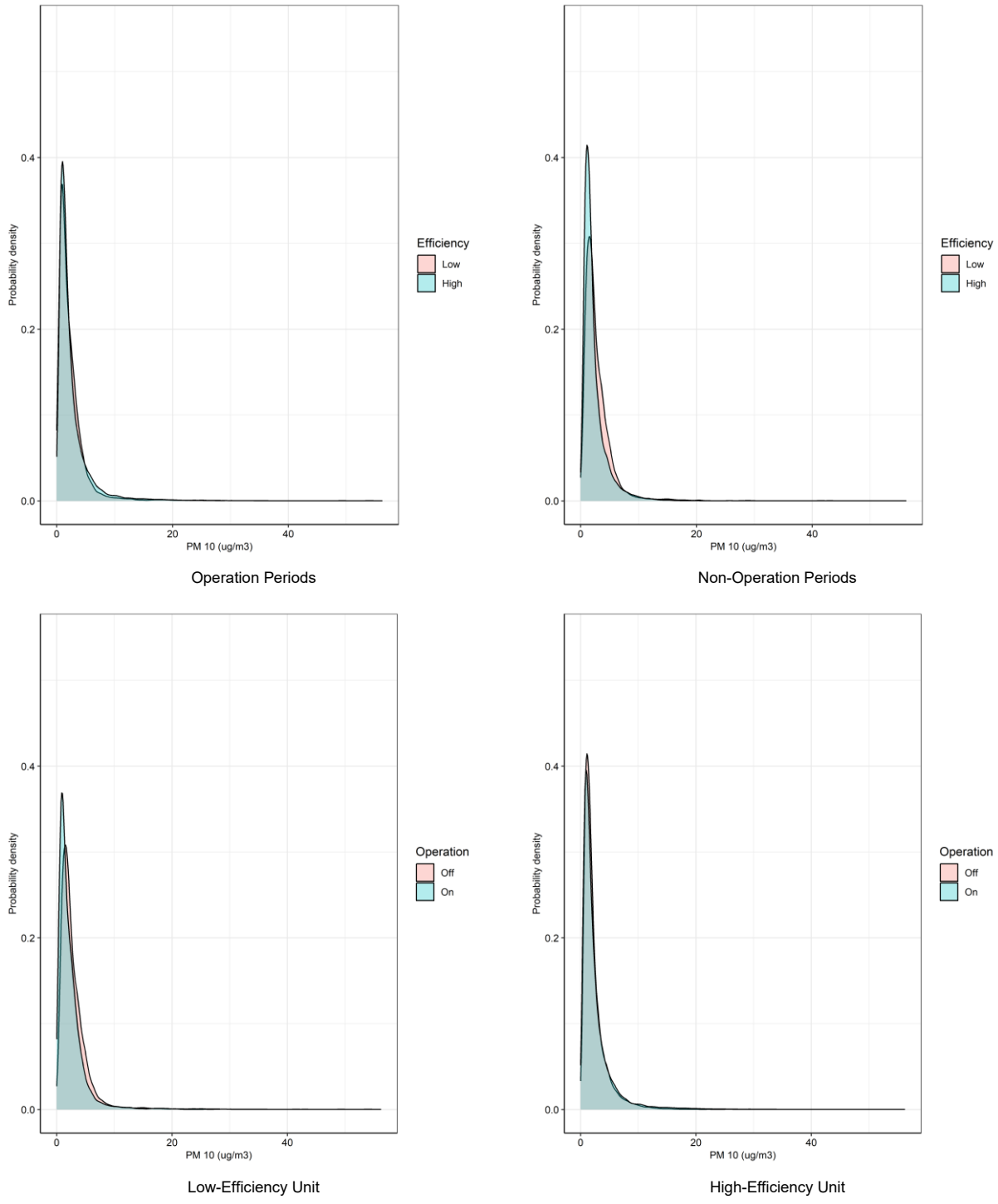

Figure F-1. DHE01 Distributions of PM_{10} concentrations during operation and non-operation

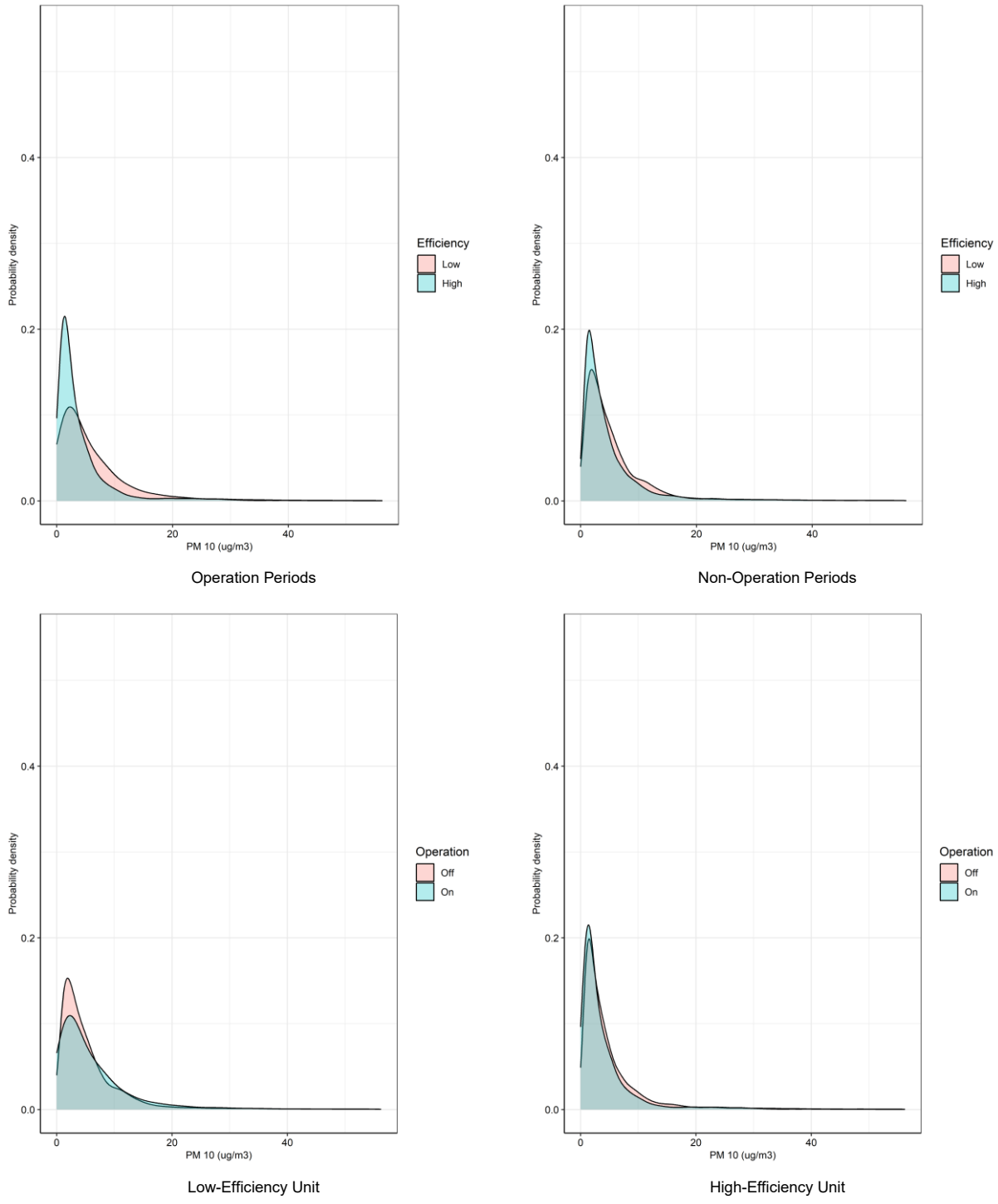

Figure F-2. DHE05 Distributions of PM_{10} concentrations during operation and non-operation

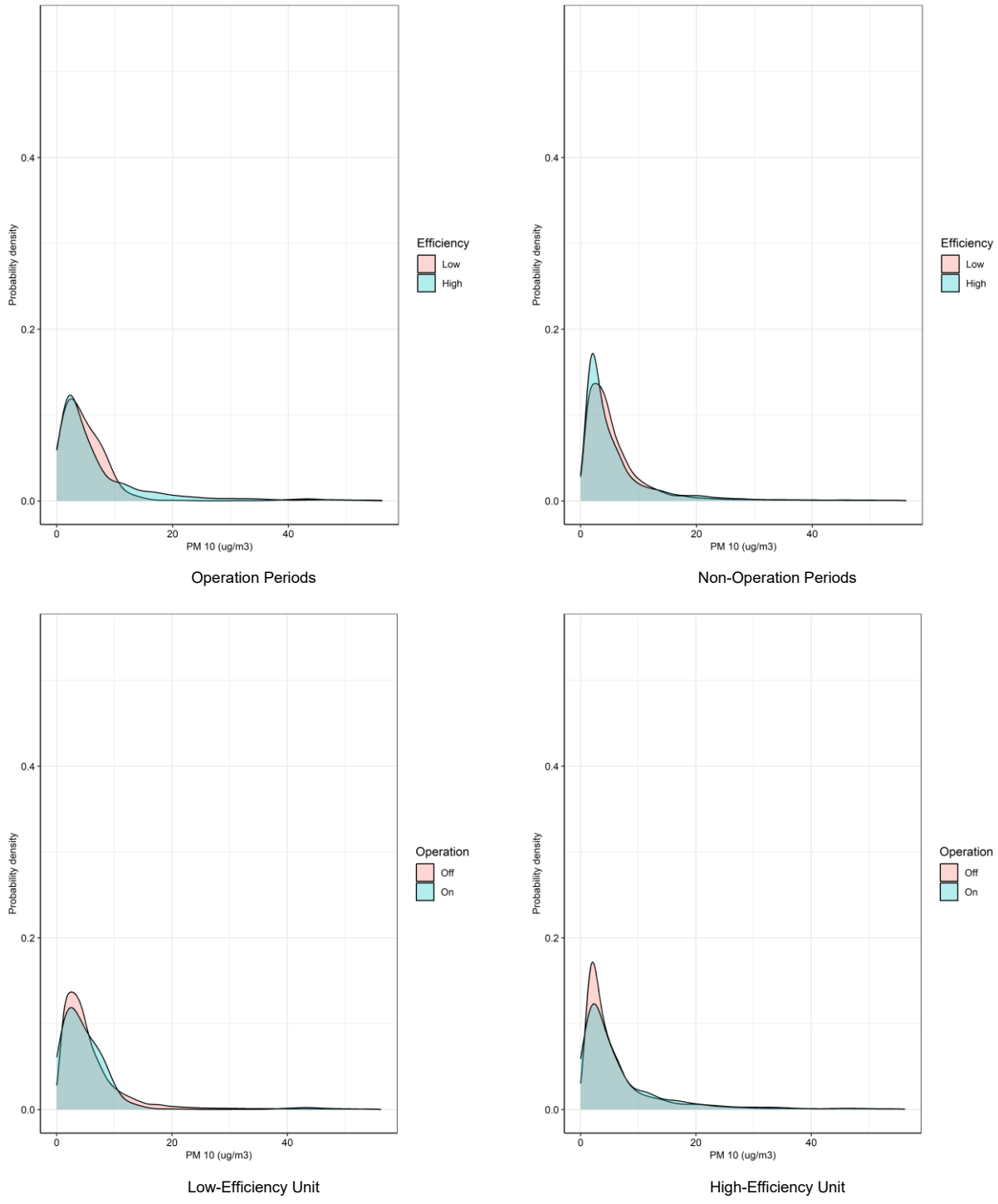

Figure F-3. DHE10 Distributions of PM_{10} concentrations during operation and non-operation

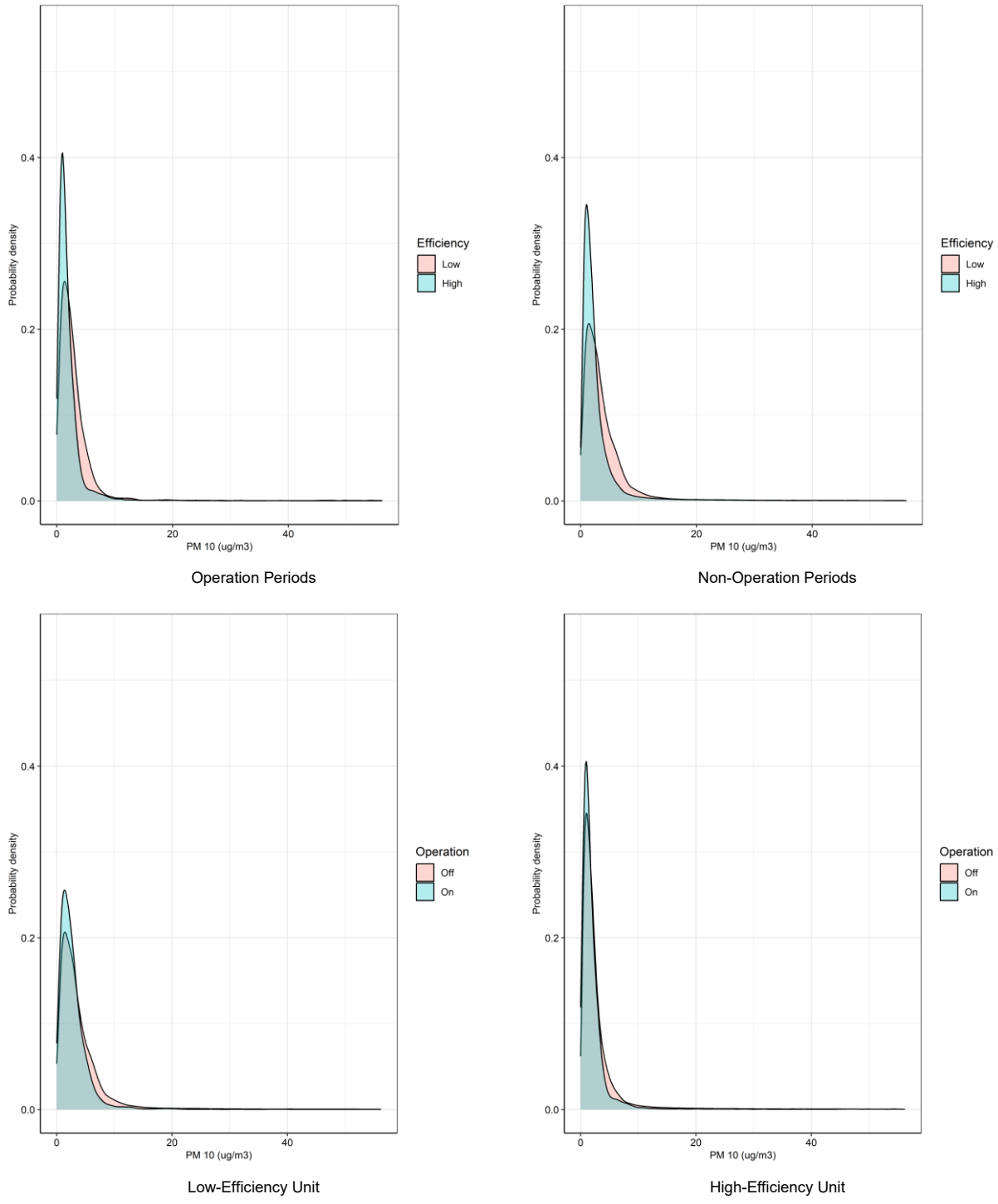

Figure F-4. DHE11 Distributions of PM_{10} concentrations during operation and non-operation

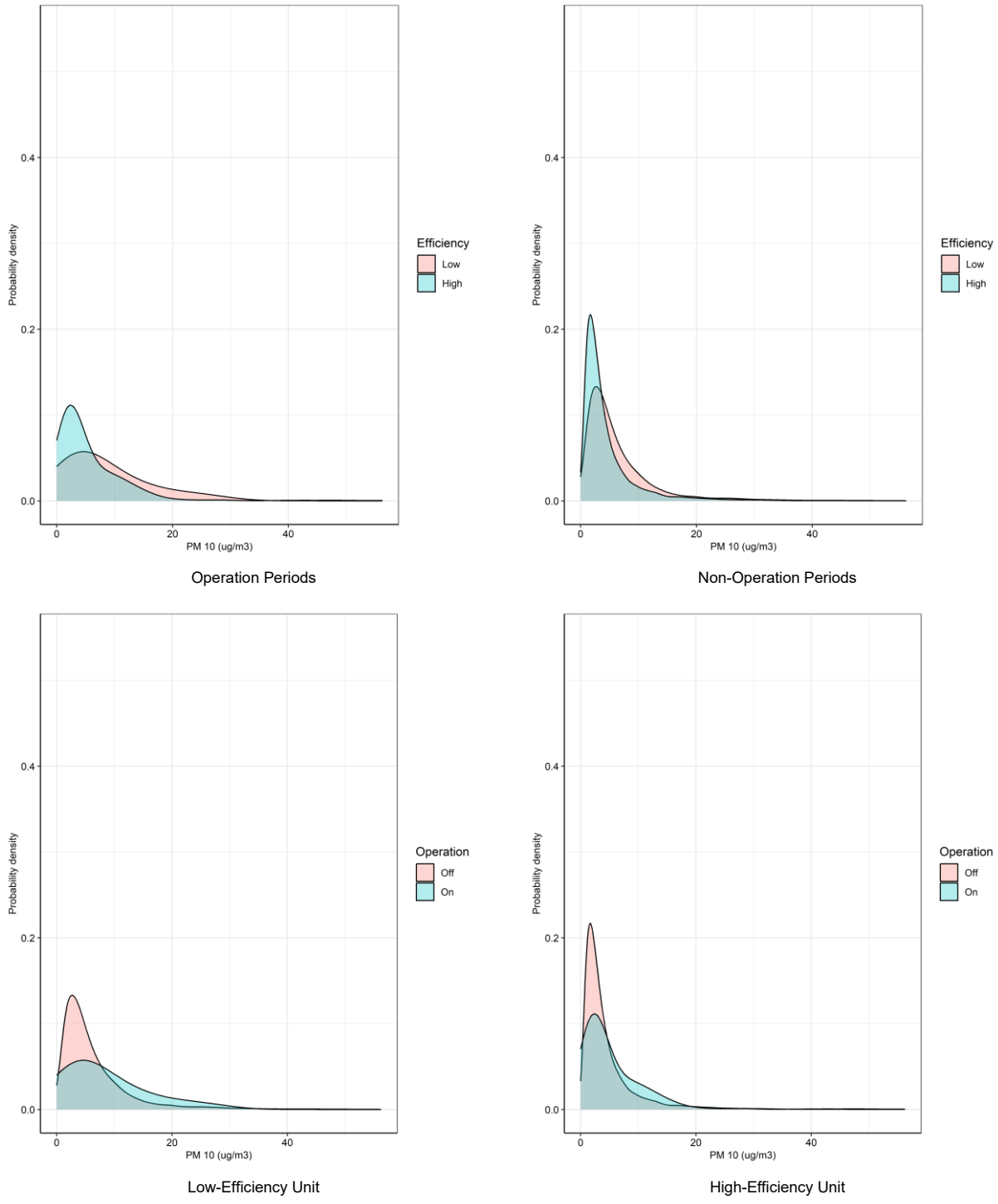

Figure F-5. DHE14 Distributions of PM_{10} concentrations during operation and non-operation

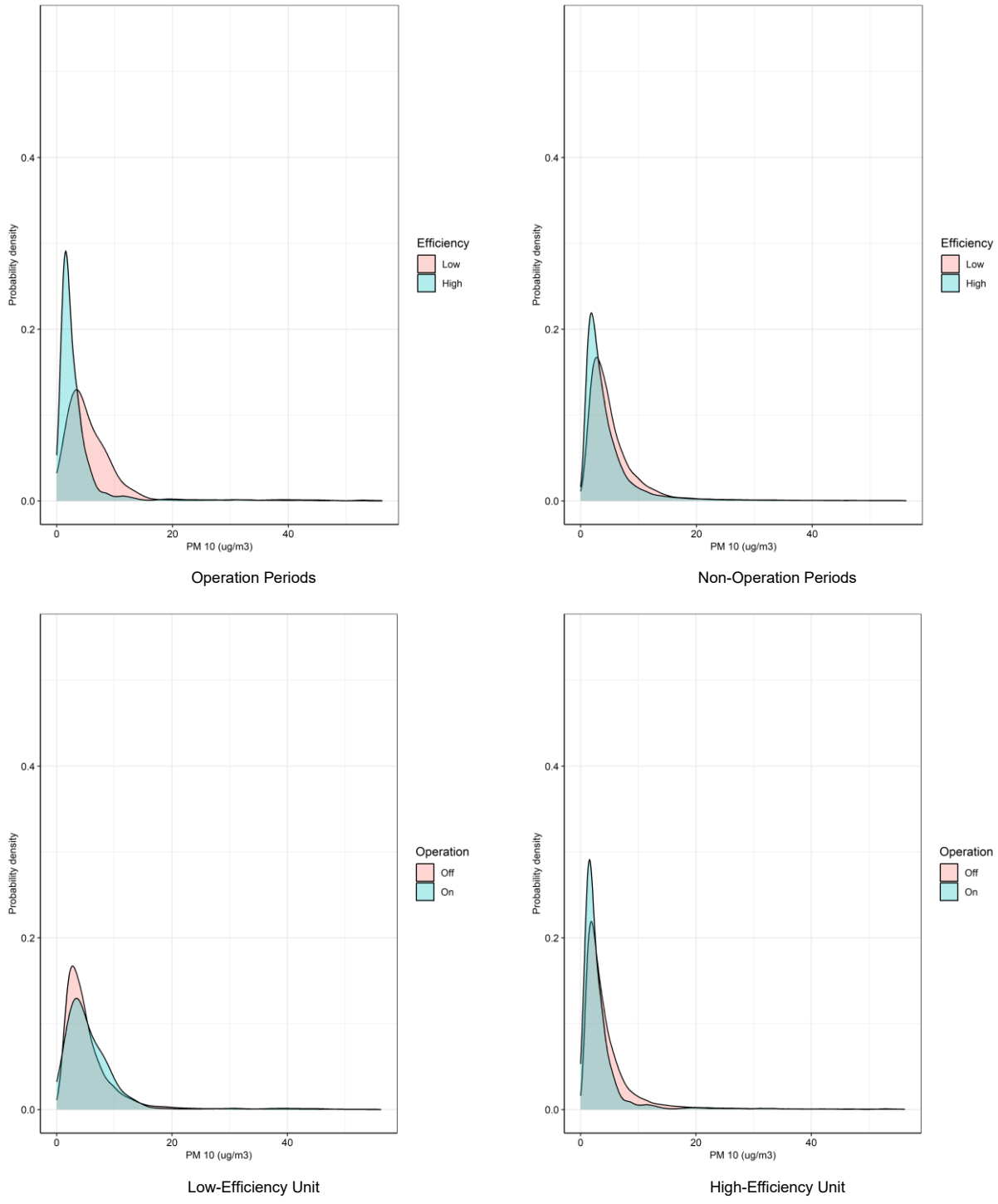

Figure F-6. DHE15 Distributions of PM_{10} concentrations during operation and non-operation

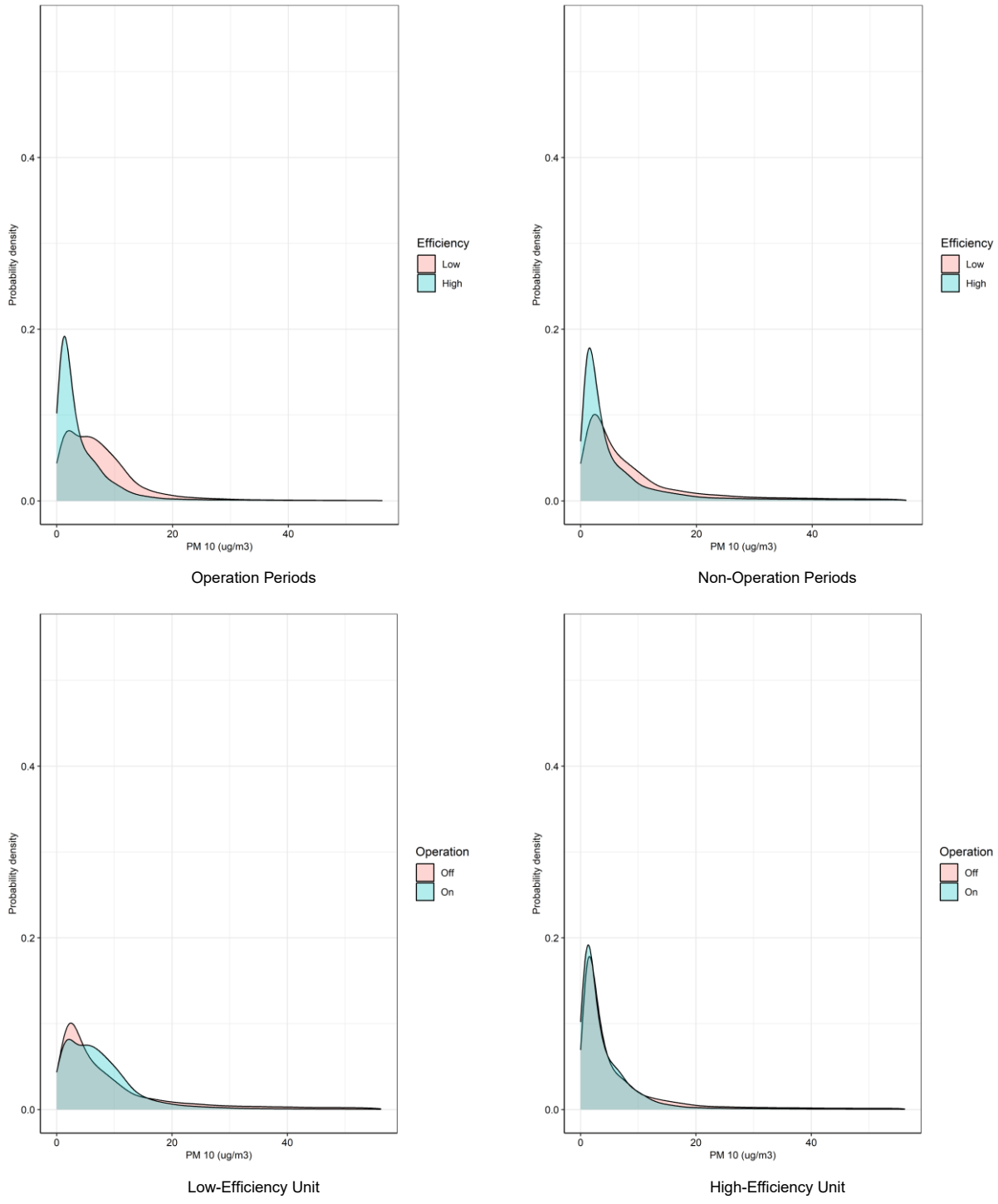

Figure F-7. DHE16 Distributions of PM_{10} concentrations during operation and non-operation

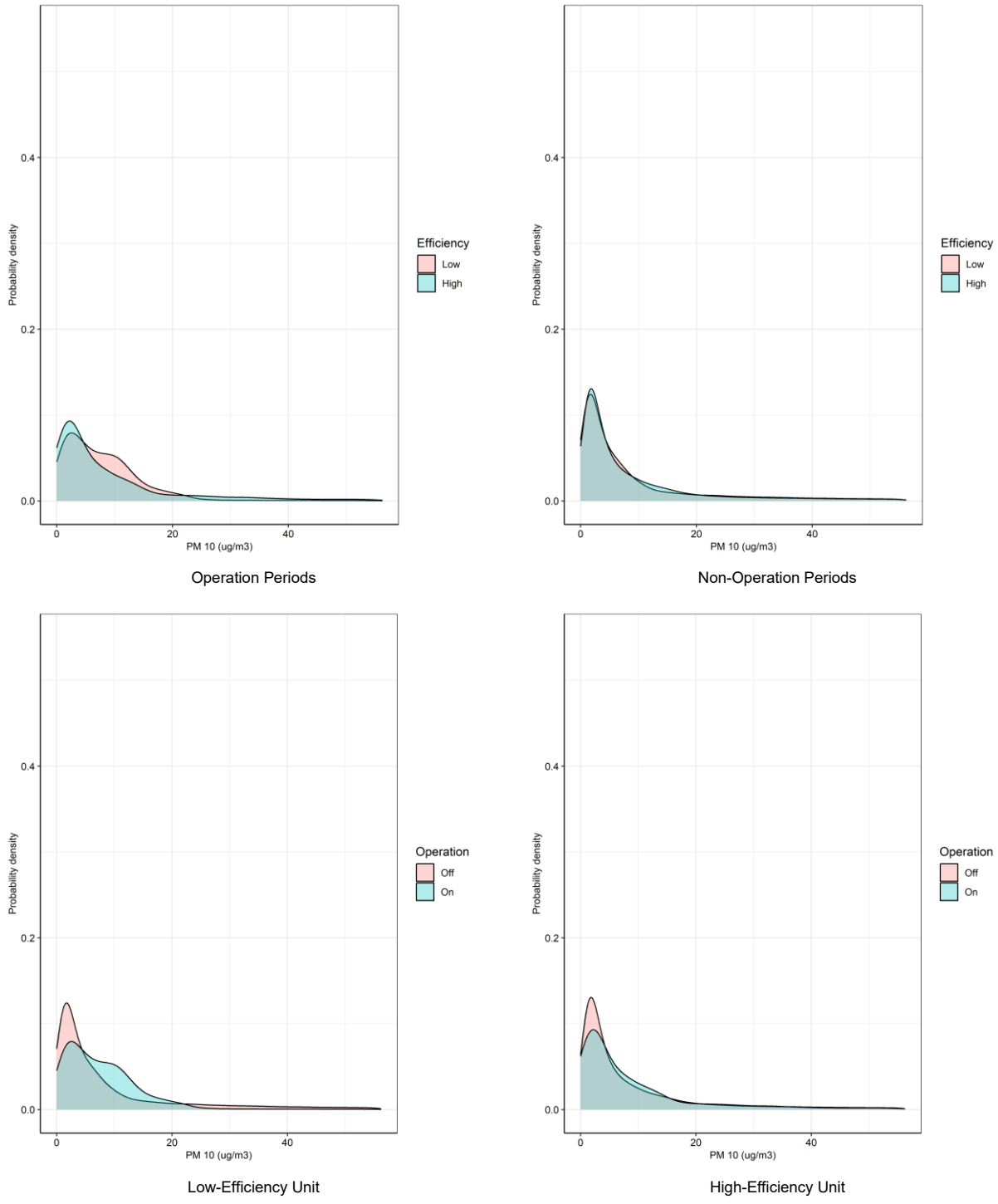

Figure F-8. DHE18 Distributions of PM_{10} concentrations during operation and non-operation

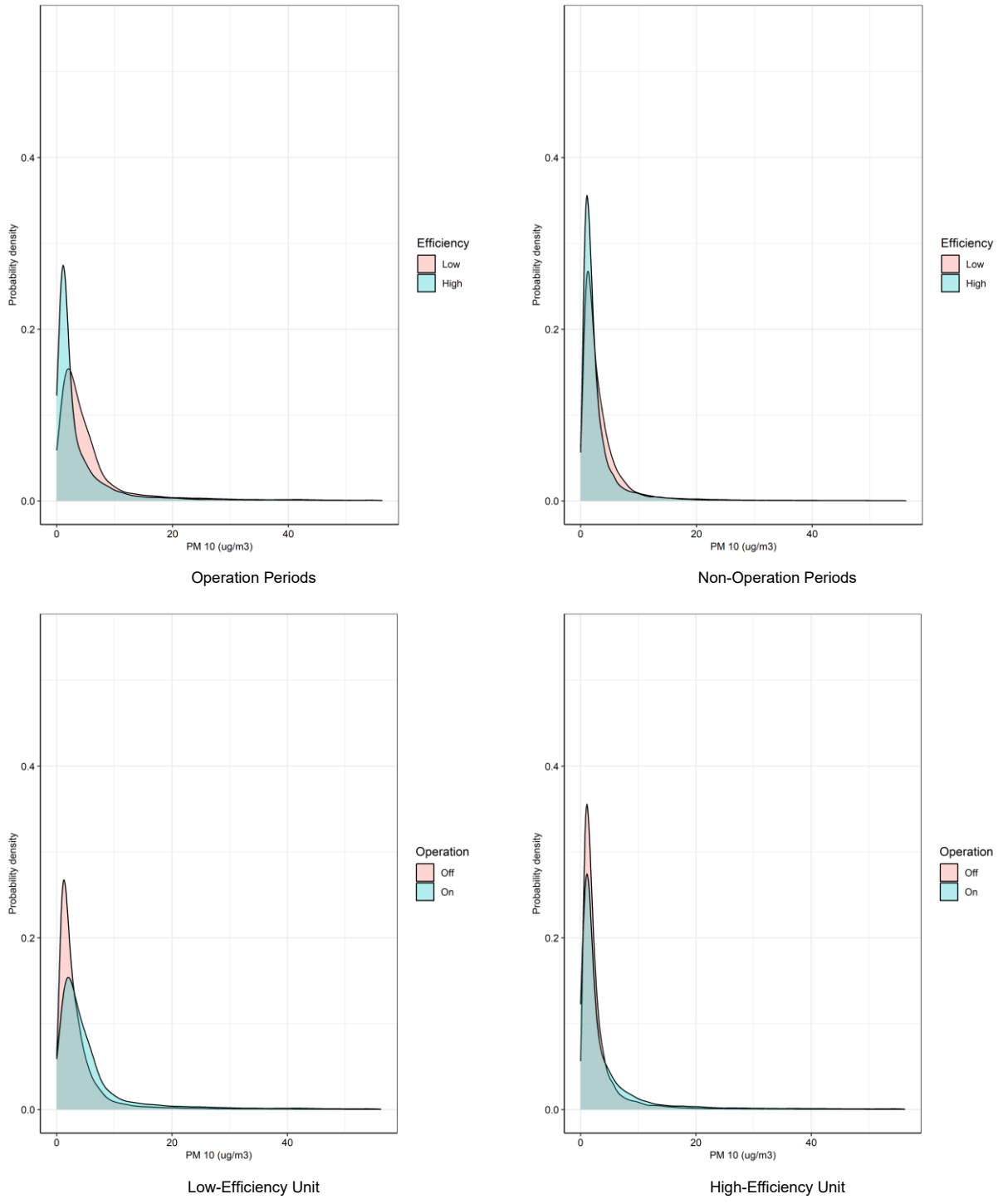

Figure F-9. DHE19 Distributions of PM_{10} concentrations during operation and non-operation

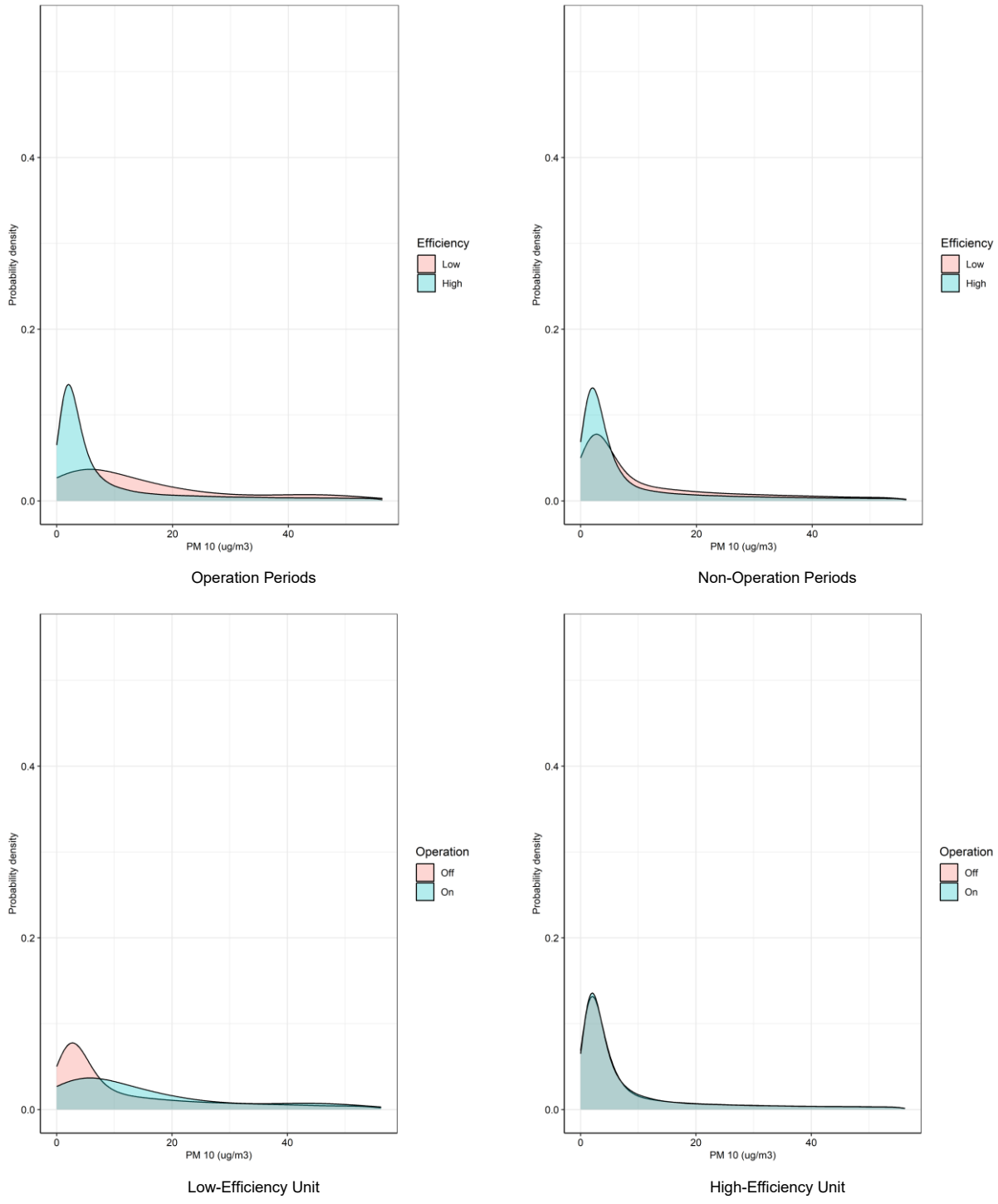

Figure F-10. DHE22 Distributions of PM_{10} concentrations during operation and non-operation

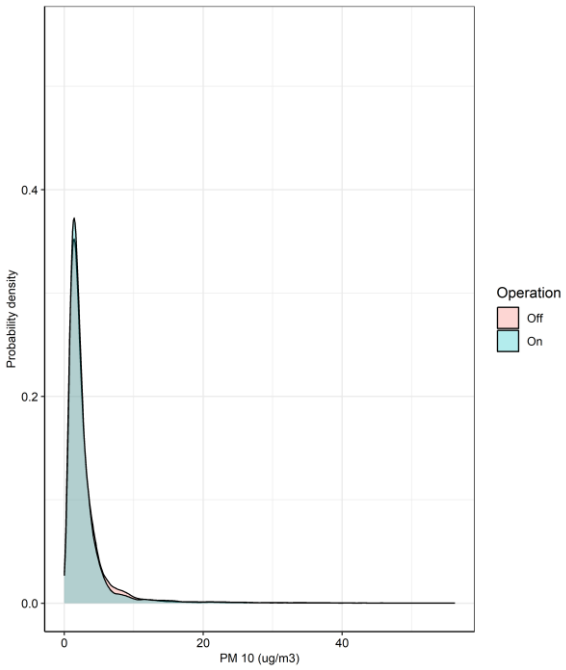

Figure F-11. DHEFF Distributions of PM_{10} concentrations during operation and non-operation

Appendix G: TVOC Concentration in Direct-Heated Spaces During Operation and Non-Operation

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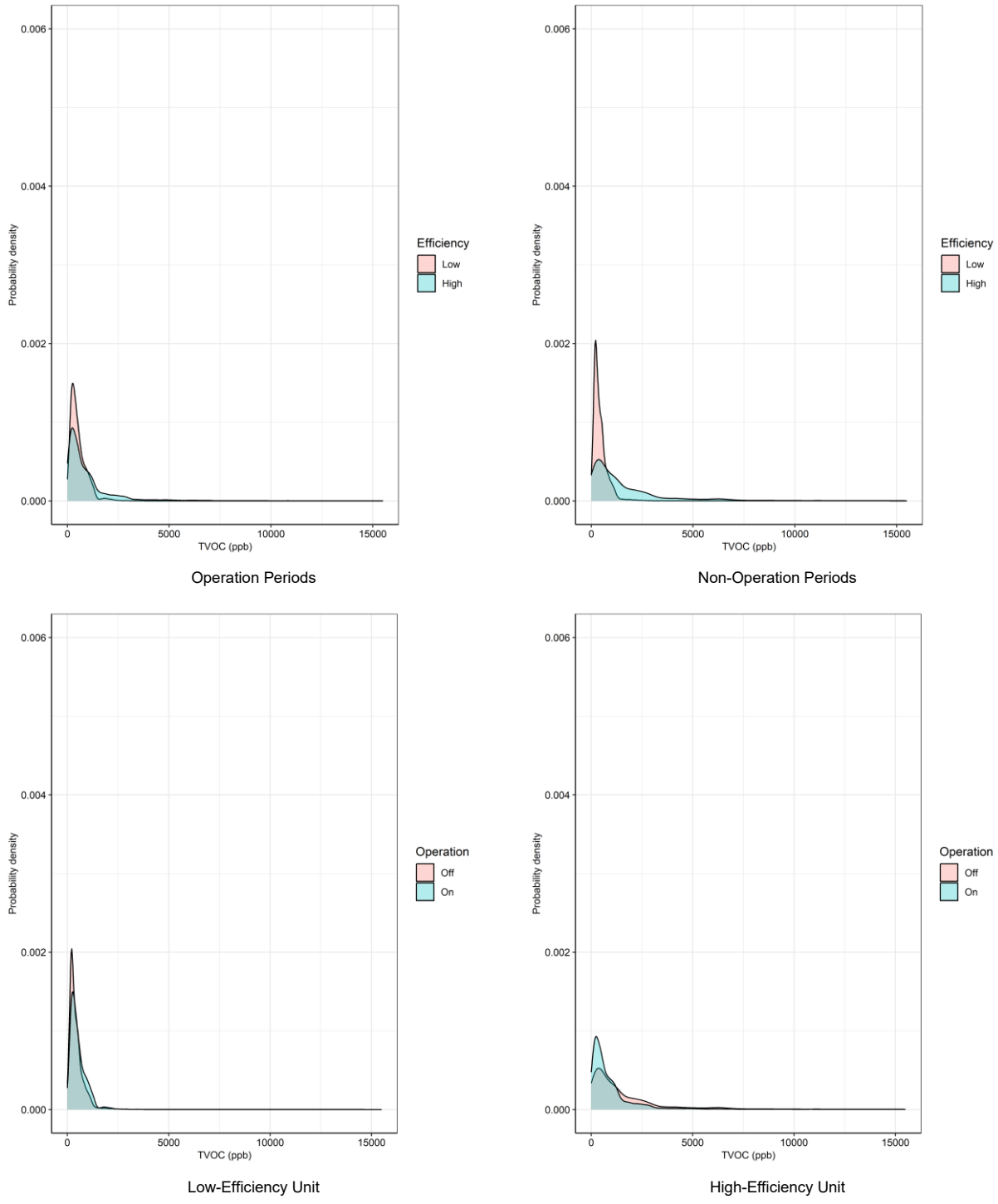

Figure G-1. DHE01 Distributions of TVOC concentrations during operation and non-operation

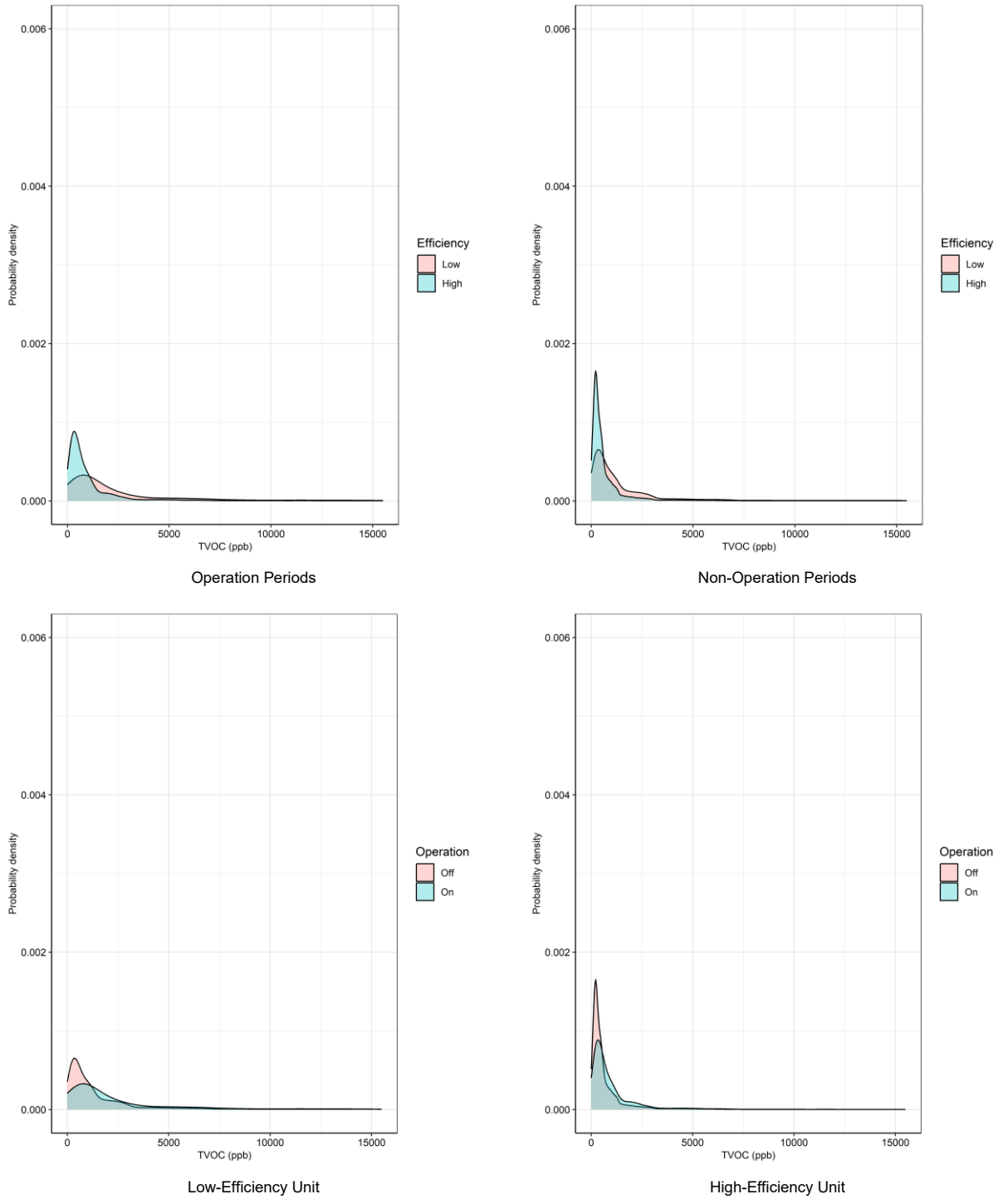

Figure G-2. DHE05 Distributions of TVOC concentrations during operation and non-operation

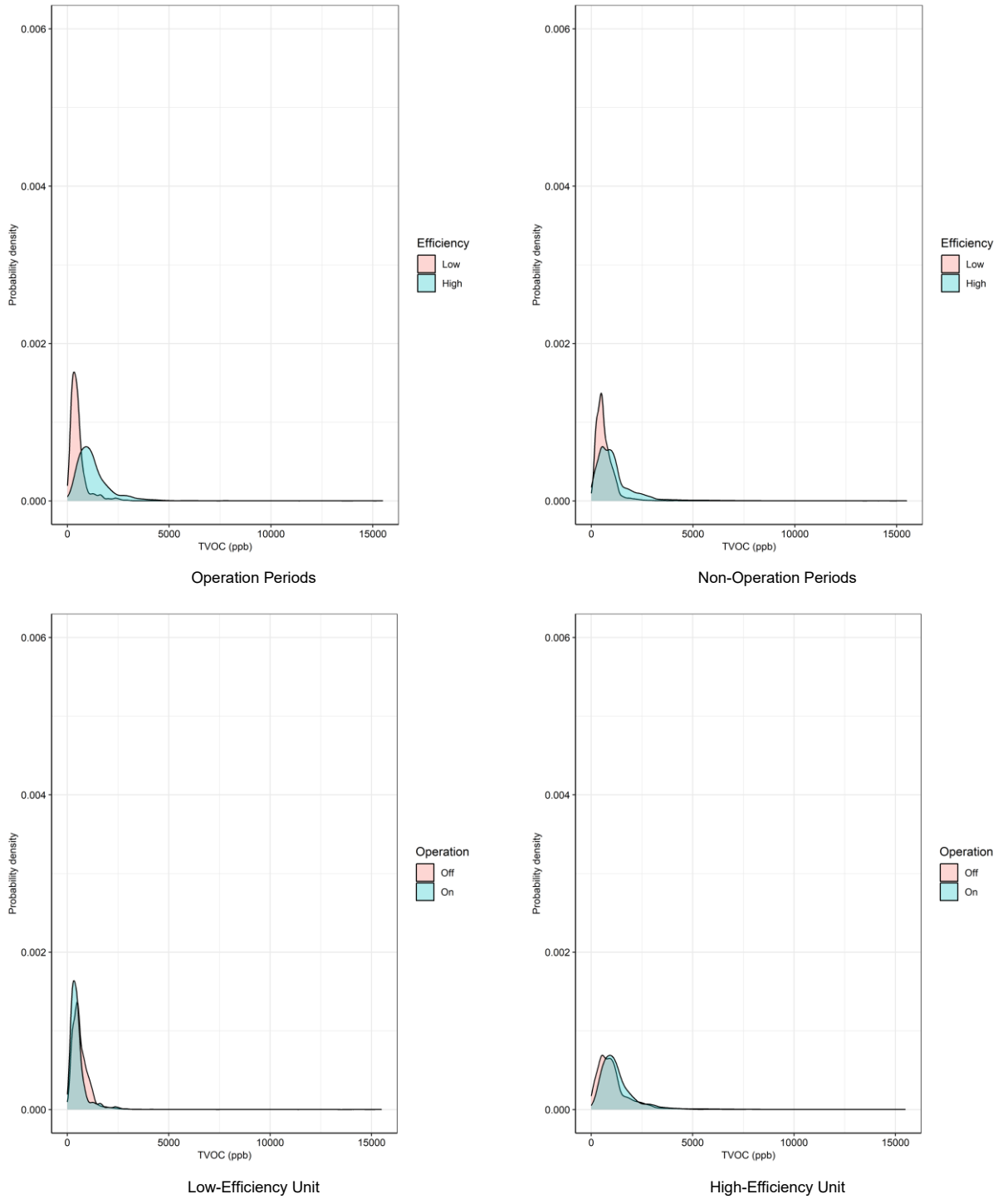

Figure G-3. DHE10 Distributions of TVOC concentrations during operation and non-operation

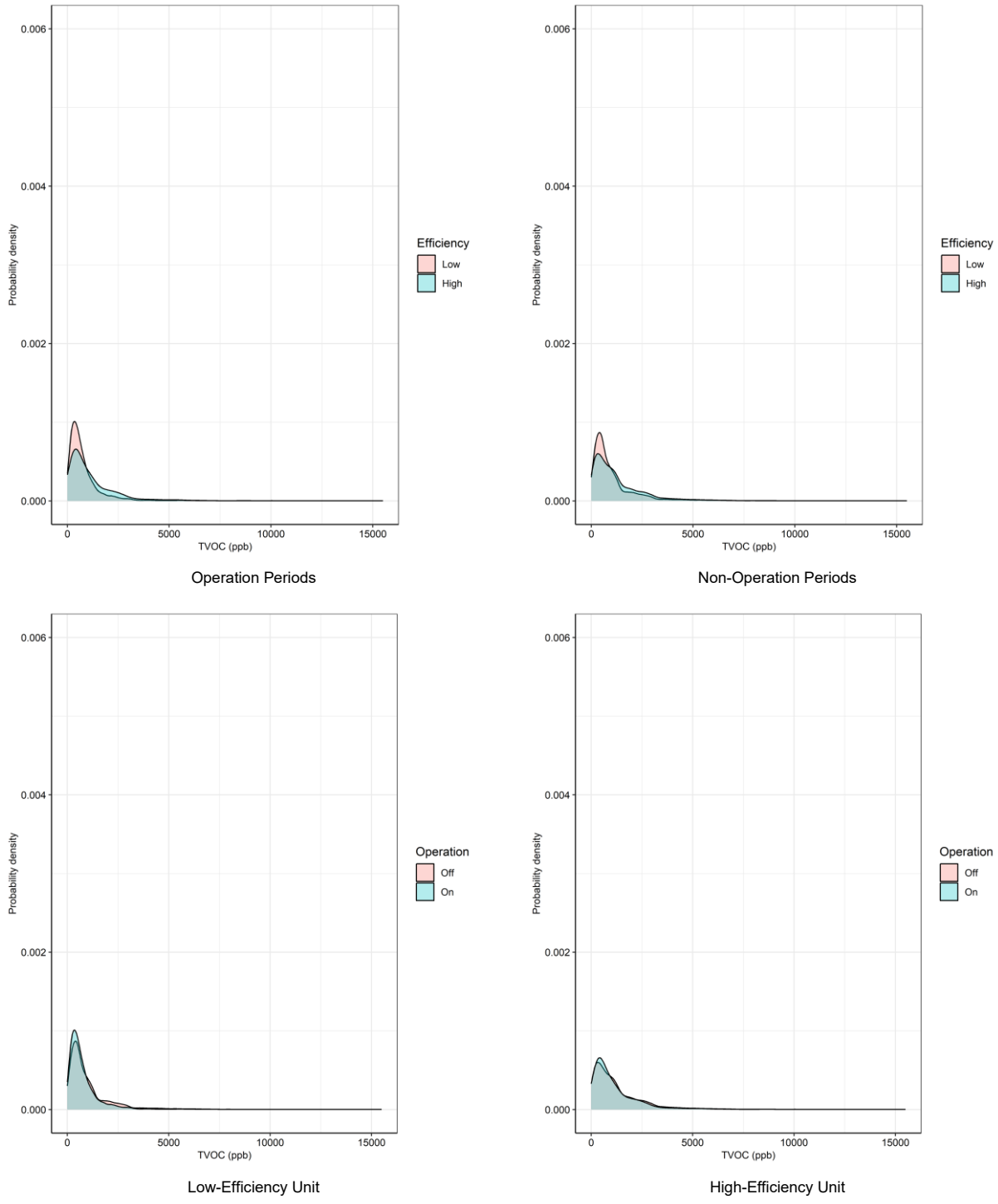

Figure G-4. DHE11 Distributions of TVOC concentrations during operation and non-operation

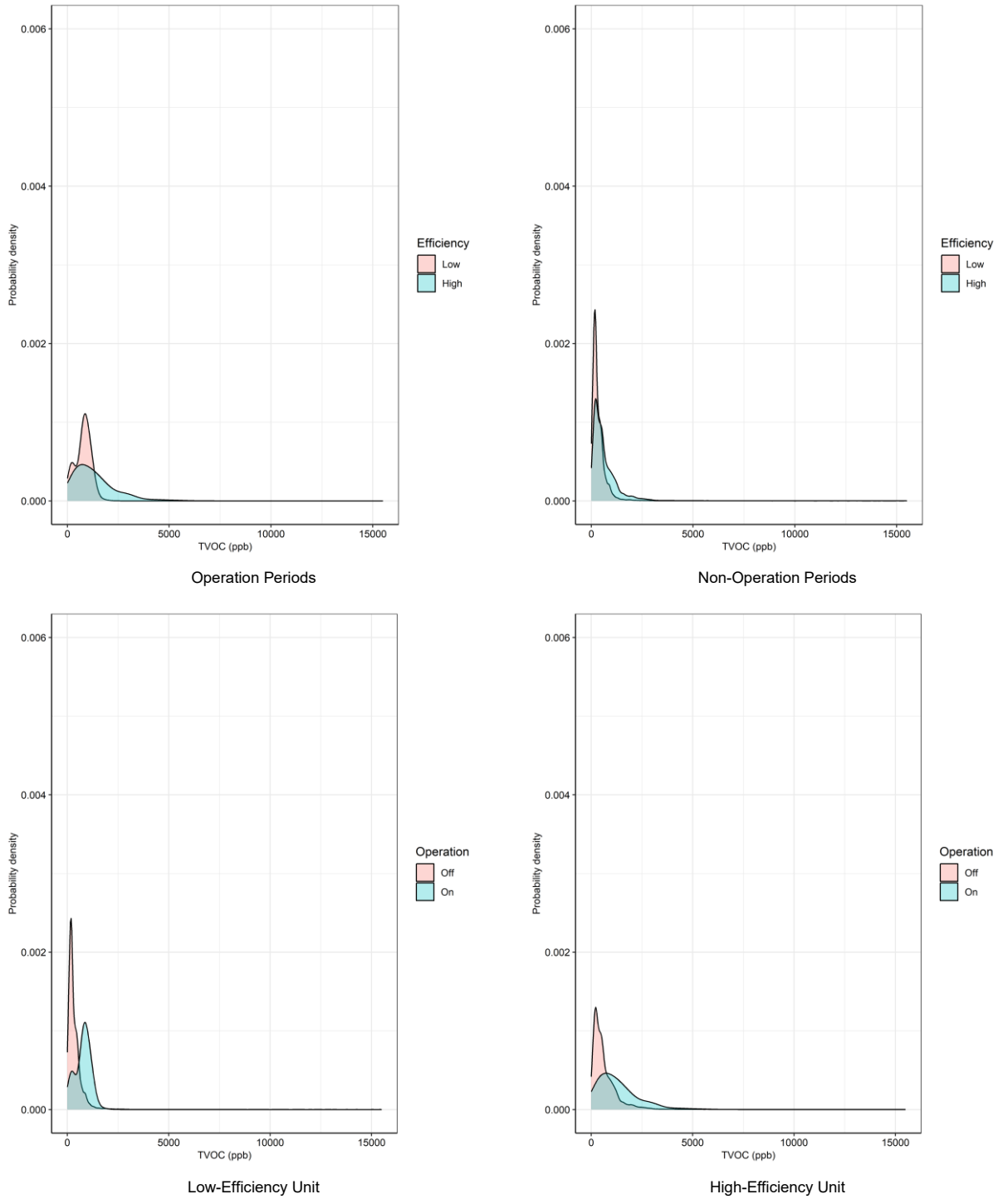

Figure G-5. DHE14 Distributions of TVOC concentrations during operation and non-operation

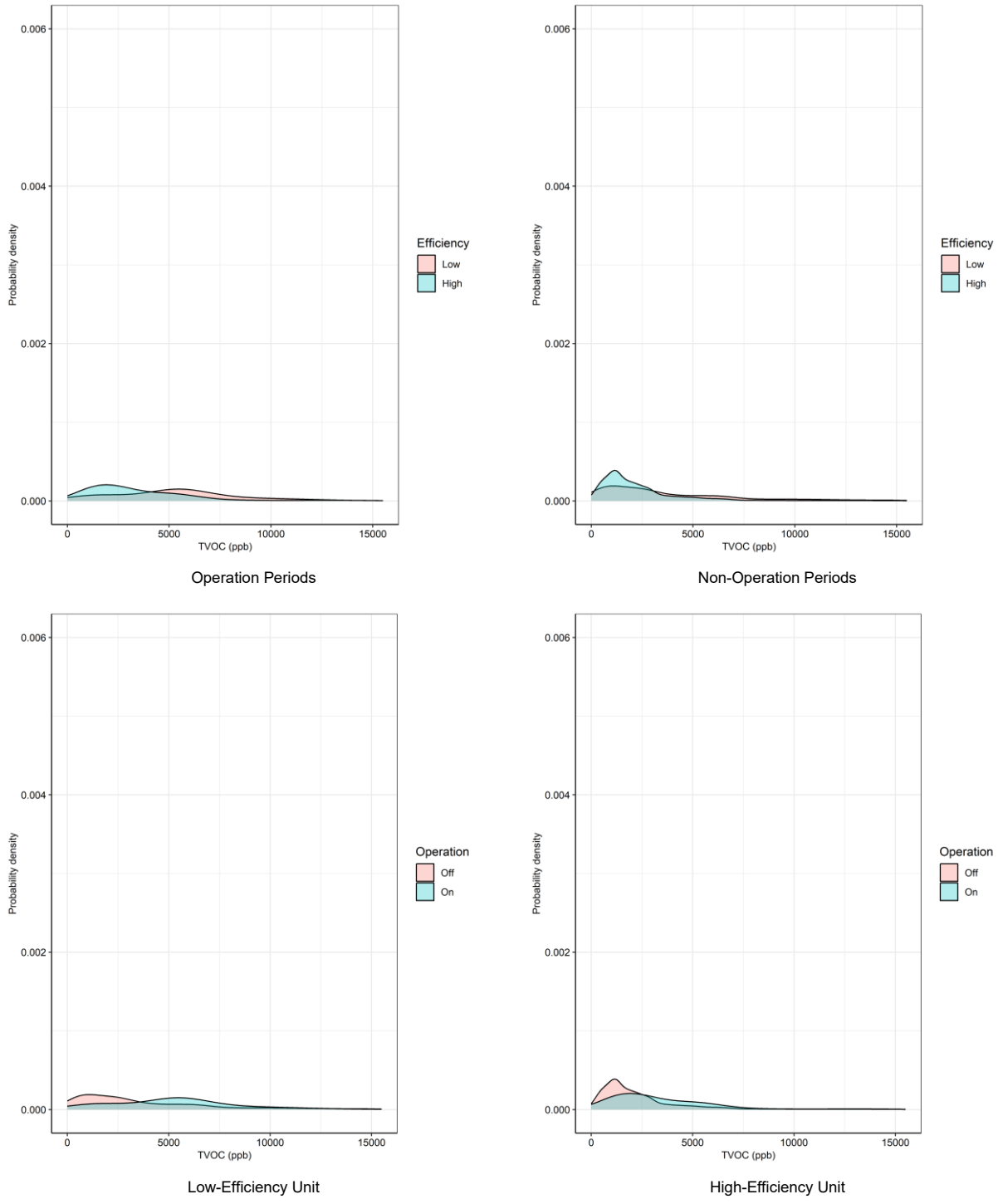

Figure G-6. DHE15 Distributions of TVOC concentrations during operation and non-operation

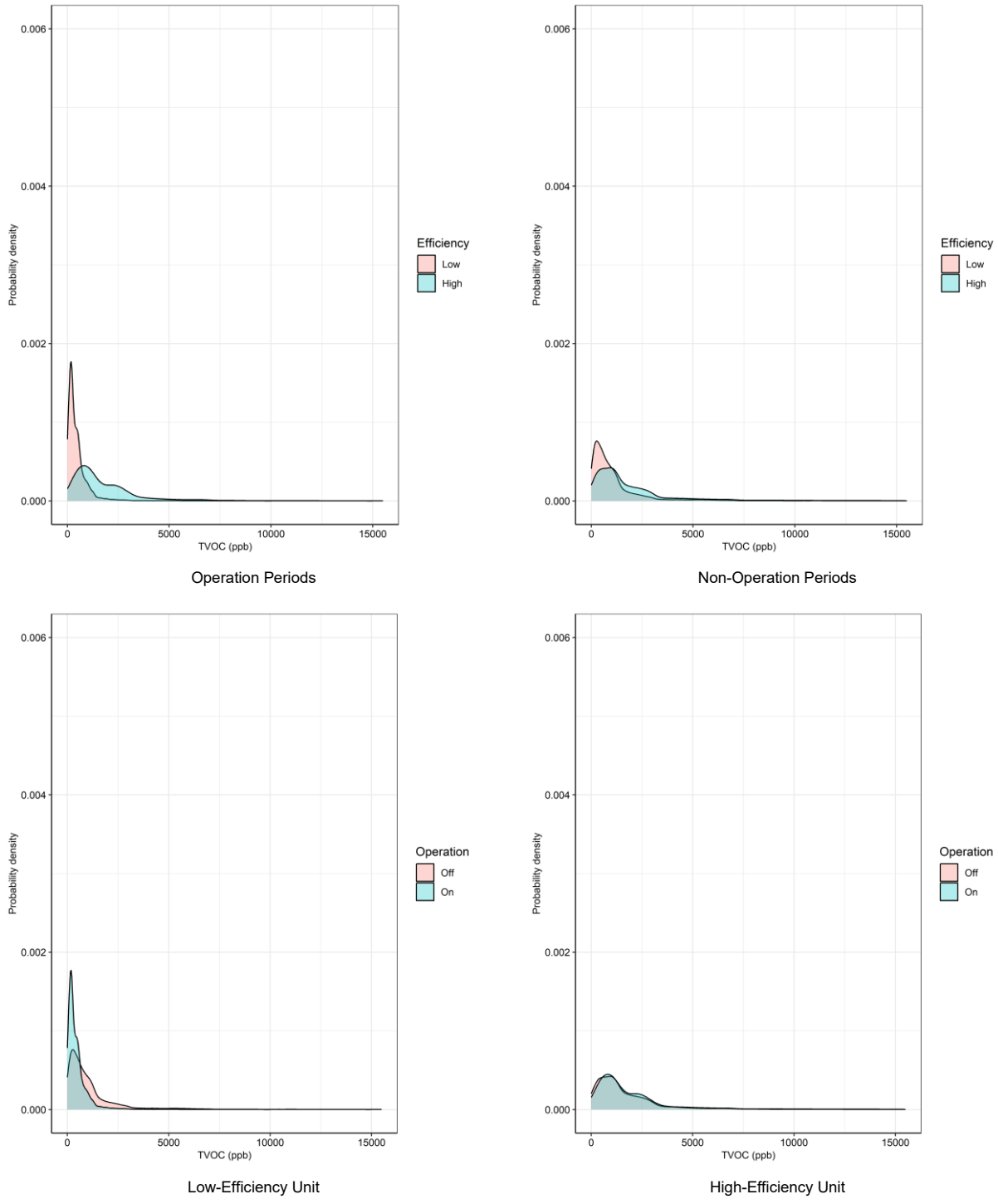

Figure G-7. DHE16 Distributions of TVOC concentrations during operation and non-operation

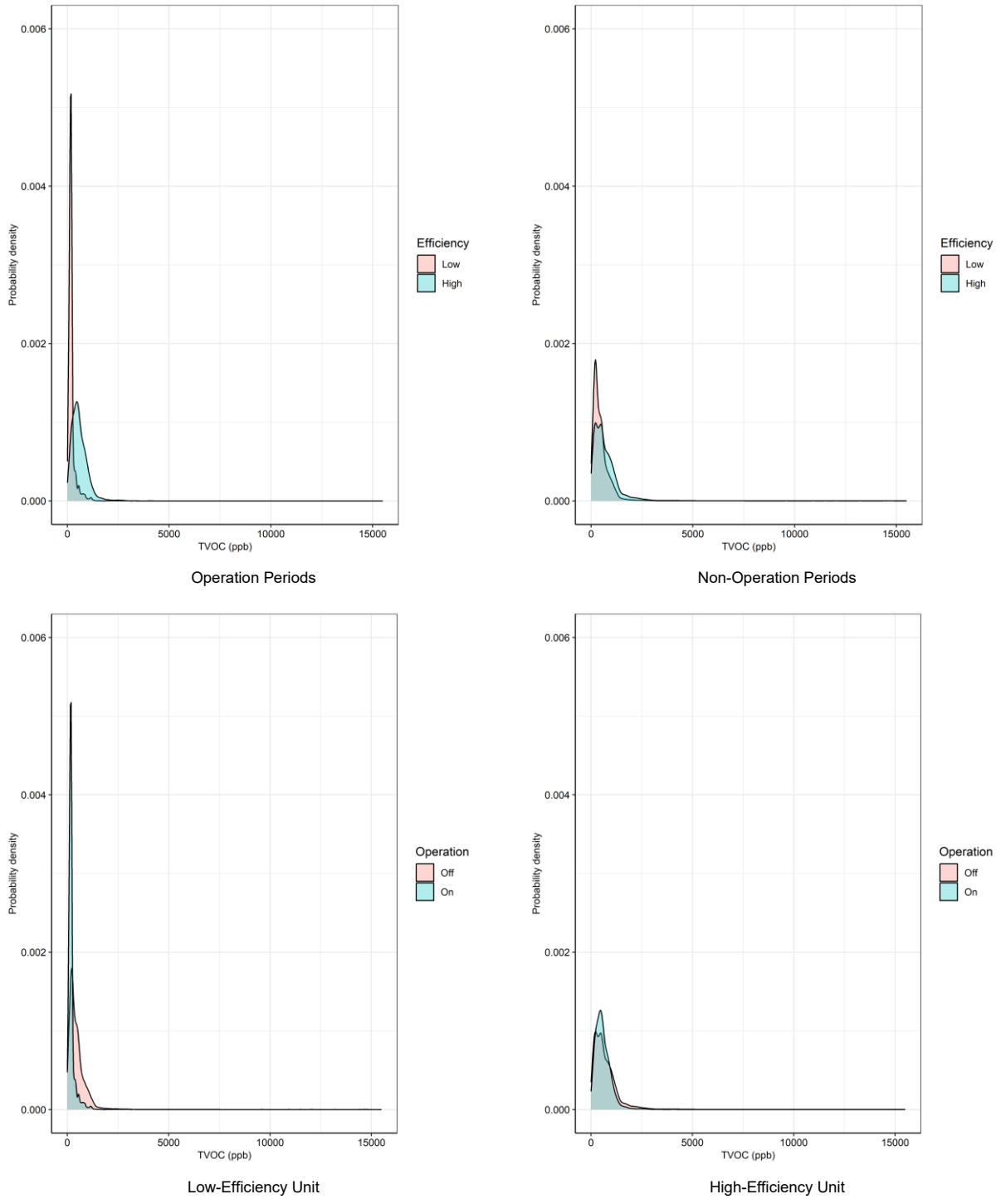

Figure G-8. DHE18 Distributions of TVOC concentrations during operation and non-operation

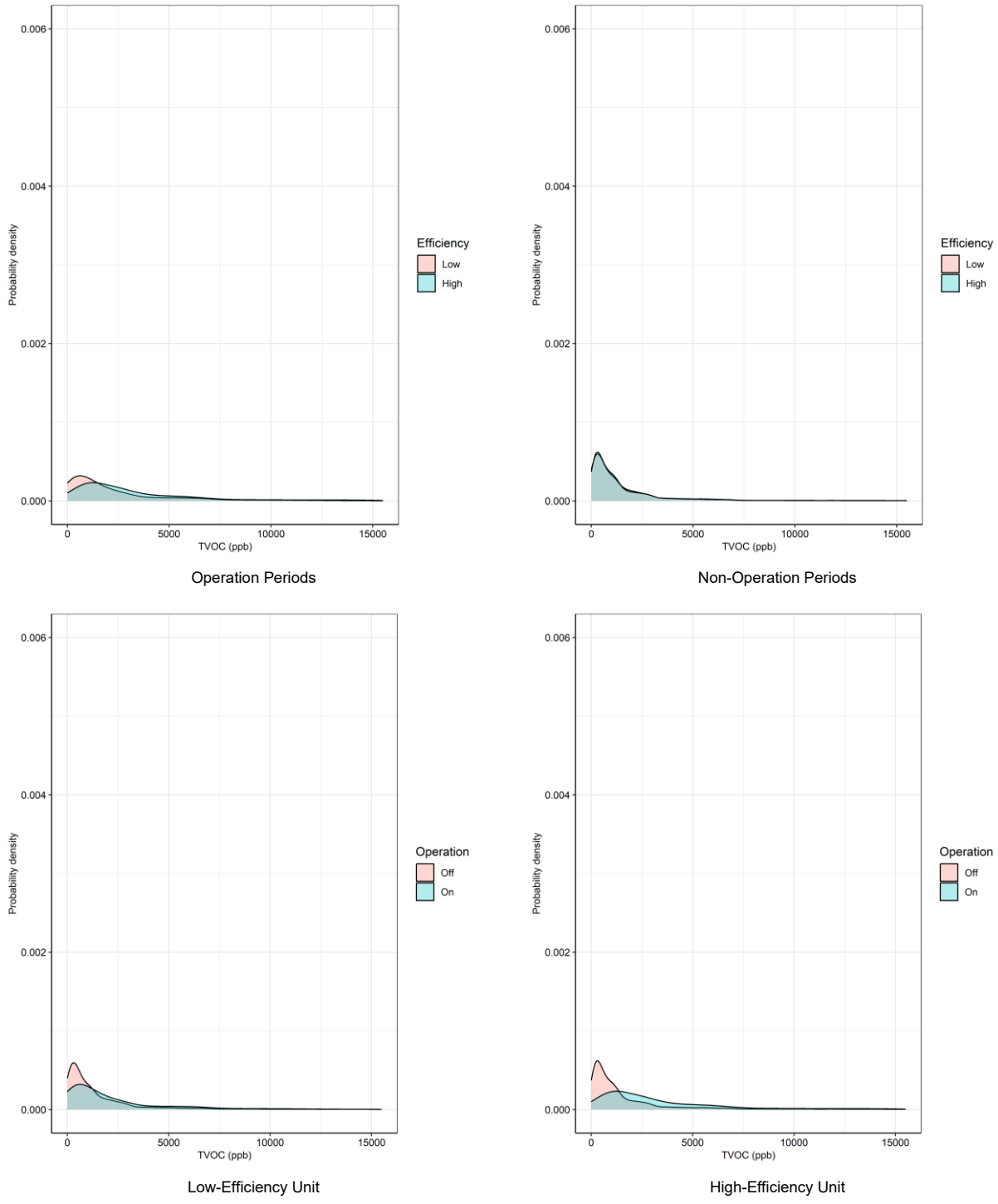

Figure G-9. DHE19 Distributions of TVOC concentrations during operation and non-operation

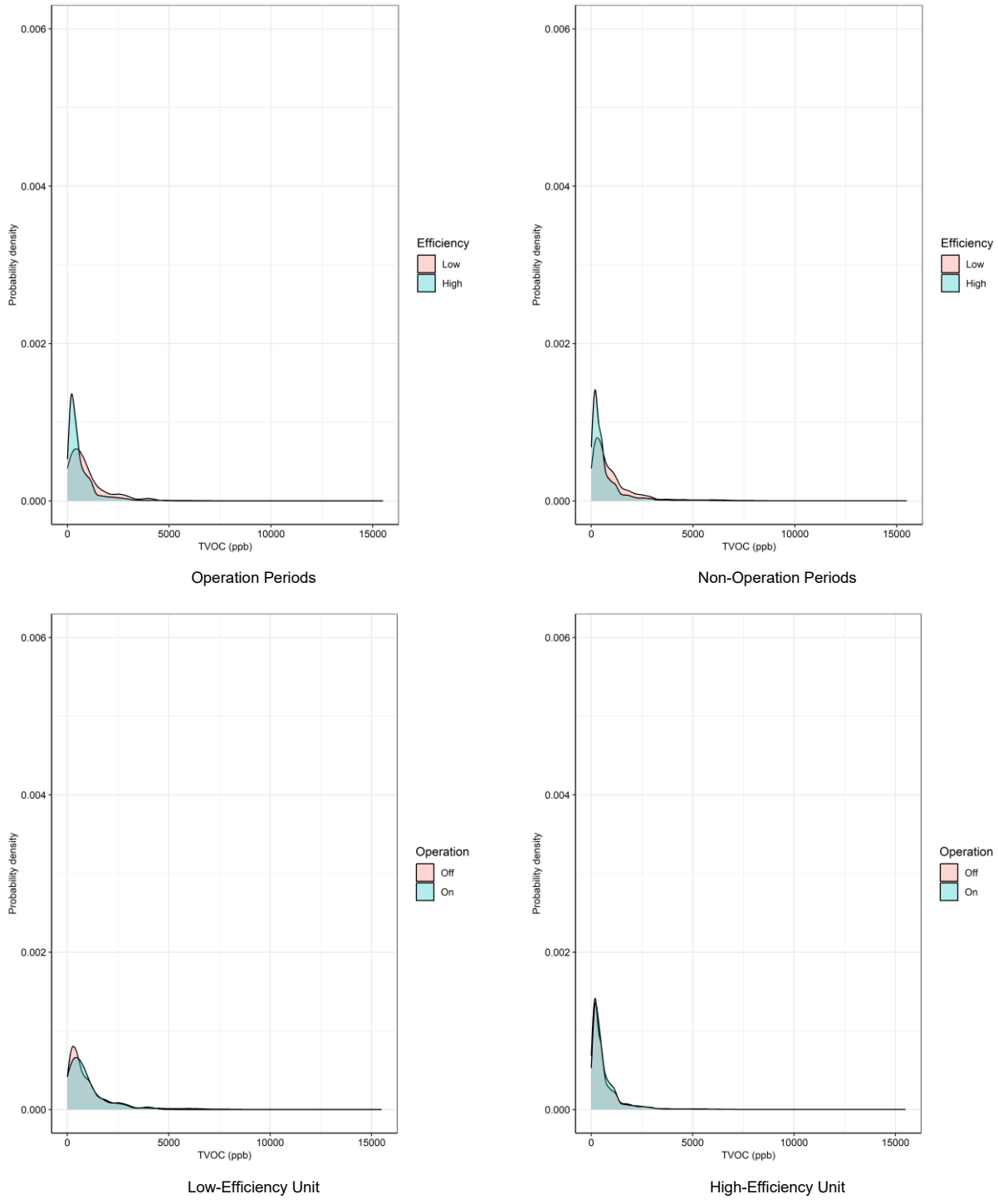

Figure G-10. DHE22 Distributions of TVOC concentrations during operation and non-operation

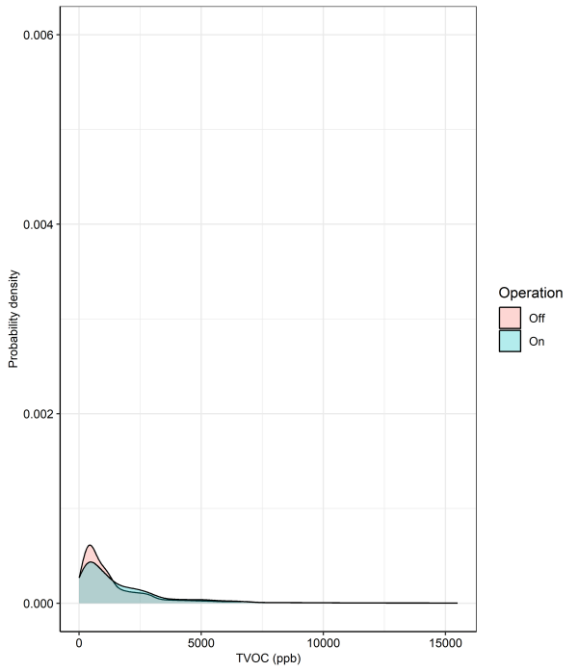

Figure G-11. DHEFF Distributions of TVOC concentrations during operation and non-operation