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The Impact of an On-Demand Thermostat on Energy Consumption and Carbon Dioxide Levels in a Hawai‘i Classroom

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The Impact of an On-Demand Thermostat on Energy Consumption and Carbon Dioxide Levels in a Hawaiʻi Classroom

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1 Report Summary

This report is a follow-on report on previous research conducted on the University of Hawaiʻi at Mānoa FROG classrooms funded by the Office of Naval Research. The 2020 COVID-19 pandemic reinforced the importance of indoor air quality (IAQ) with respect to natural ventilation and mechanical space conditioning. The report has three primary objectives that evaluate energy and indoor air quality with natural and mechanical ventilation mechanisms. The objectives of this report are:

- To evaluate the energy consumption for operating heating, ventilation and air conditioning (HVAC) systems "on-demand" by limiting the run times via a thermostat override as a substitute for a traditional set-point driven thermostat. One hour, 4 hour and 8 hour run times have been monitored for this study;
- To determine the impact on CO_2 concentrations in the FROGs under varying HVAC operating hours, on-demand settings, natural ventilation and users' operation;
- To evaluate the impact of building users' post-pandemic awareness of natural ventilation mechanisms, as compared to pre-pandemic conditions.

The data was collected over a 6-year period from 2017 through 2022. In 2020-2022, the global COVID-19 pandemic revealed a new relevance to natural ventilation and indoor air quality. The analyses and conclusions in this report reflect 2022 interpretations of the data, focusing on the importance of fresh outside air in mitigating the spread of airborne vectors such as the coronavirus, and the resulting impact on energy consumption.

2 Introduction

The buildings investigated during this study are part of previous research focusing on the energy consumption of net zero energy, mixed mode classrooms [1, 2]. The following results and discussions are based on a multiyear study on the energy and indoor air quality (specifically using carbon dioxide concentration as a proxy for IAQ) of two twin FROG 1 and FROG 2, concurrent, mixed-mode [3] standalone classroom buildings in Honolulu, Hawaiʻi, located in the hot and humid International Energy Conservation Code climate zone 1A [4]. University of Hawaiʻi at Mānoa (UHM) researchers monitored the two classrooms over six years to evaluate the energy savings associated with a unique and dedicated "on-demand" HVAC thermostat [1] while monitoring CO_2 levels and other indoor variables.

The buildings on the University of Hawaiʻi Mānoa Campus have a similar end use (education, with university and high school students). Several studies have investigated the energy performance [5], thermal comfort [6], as well as indoor air quality, ventilation, and occupant health symptoms [7] of school buildings, but the majority of the studies were located in temperate climates rather than tropical ones. The typical occupant density in a school classroom is commonly high and dynamic when compared to an office building [8] and the metabolic gains are also high [9]. Thus, this study investigates how similar end-users can use the same mixed-mode buildings differently and how CO_2 levels can be impacted by user choices and of heating, ventilation and air conditioning "on-demand" thermostat settings.

3 Methods

3.1 Description of the FROG buildings

The two identical 134 m^2 (1,440 ft^2) classroom buildings were constructed on the UHM campus in 2015–2016 to test building design and fabrication strategies, and to research new technologies and energy control systems. The structures are component-based and were assembled on site (Figure 1).

Figure 1. *FROG 1 and FROG 2 at the University of Hawaiʻi at Mānoa. Photos by University of Hawaiʻi.*

The envelope design integrates basic energy efficient concepts (Table 1) including north and south orientation to minimize solar gain; overhangs to further shield the high performance, low-e glazing to minimize solar gain; and the walls and roofs that are well insulated. LED lighting with daylight harvesting controls that optimize lighting levels according to the amount of daylighting are part of the integrated design. The heating, ventilation and air conditioning (HVAC) system is designed for mixed-mode performance, meaning that either natural ventilation or mechanical air conditioning can be used to maintain indoor comfort. These single-room classroom buildings were equipped with split-system, direct expansion air-conditioning units with supply air delivered at slightly higher than normal temperatures in order to avoid condensation on the supply registers because of higher room humidity levels. These buildings were not designed with automated window actuators or HVAC interlocks.

3.1.1 On-demand Thermostat

The UHM FROGS were designed with a unique "on-demand" control that limits the operation of an HVAC system to be used only when the user requests it, rather than be automatically scheduled to run during normal operating hours regardless of whether the room is occupied or not. The on demand thermostat requires users to make a conscious decision to turn the air conditioning (AC) ON (i.e., a user preference), which allows the unit to run for a fixed number of hours (initially 1 hour, then 8 hours, and later 4 hours only) then turn OFF automatically. When the interior comfort conditions require that it be restarted, the ON button is pressed once again to reenergize for another defined period. An on-demand control reduces the HVAC run time when there are no occupants in the buildings [2]. In addition, the on-demand control requires user engagement and decision-making (called technological or environmental adjustment as stated by [10], increasing awareness of building operations. Variable speed ceiling fans increase the air movement inside the buildings. Previous studies in the tropics showed that air movement increases the range of temperatures in which people feel comfortable [11, 12, 13]. The interior conditions of the FROGs were highly dependent upon the knowledge and preference of the user to choose between using natural ventilation, concurrent ceiling fans and/or activating the mechanical cooling and ventilation using on-demand controls.

In classroom situations where there may be long intervals between classes, the on-demand control results in significant savings because the AC will not run if there is no one in the class to reactivate the auto-off AC. A previous study showed an 84% reduction in energy consumption beyond a conventional thermostat scheduled for 7 am to 7 pm operation [2] when on a 1-hr demand override setting when a non-sequential classroom schedule is in place. To add value as research platforms intended to help educate users about the building's response to energy efficient design, the UHM FROG classrooms incorporated a real-time dashboard that displayed current and past operating conditions, including indoor comfort indicators (CO_2), renewable energy generation as well as the end uses of energy.

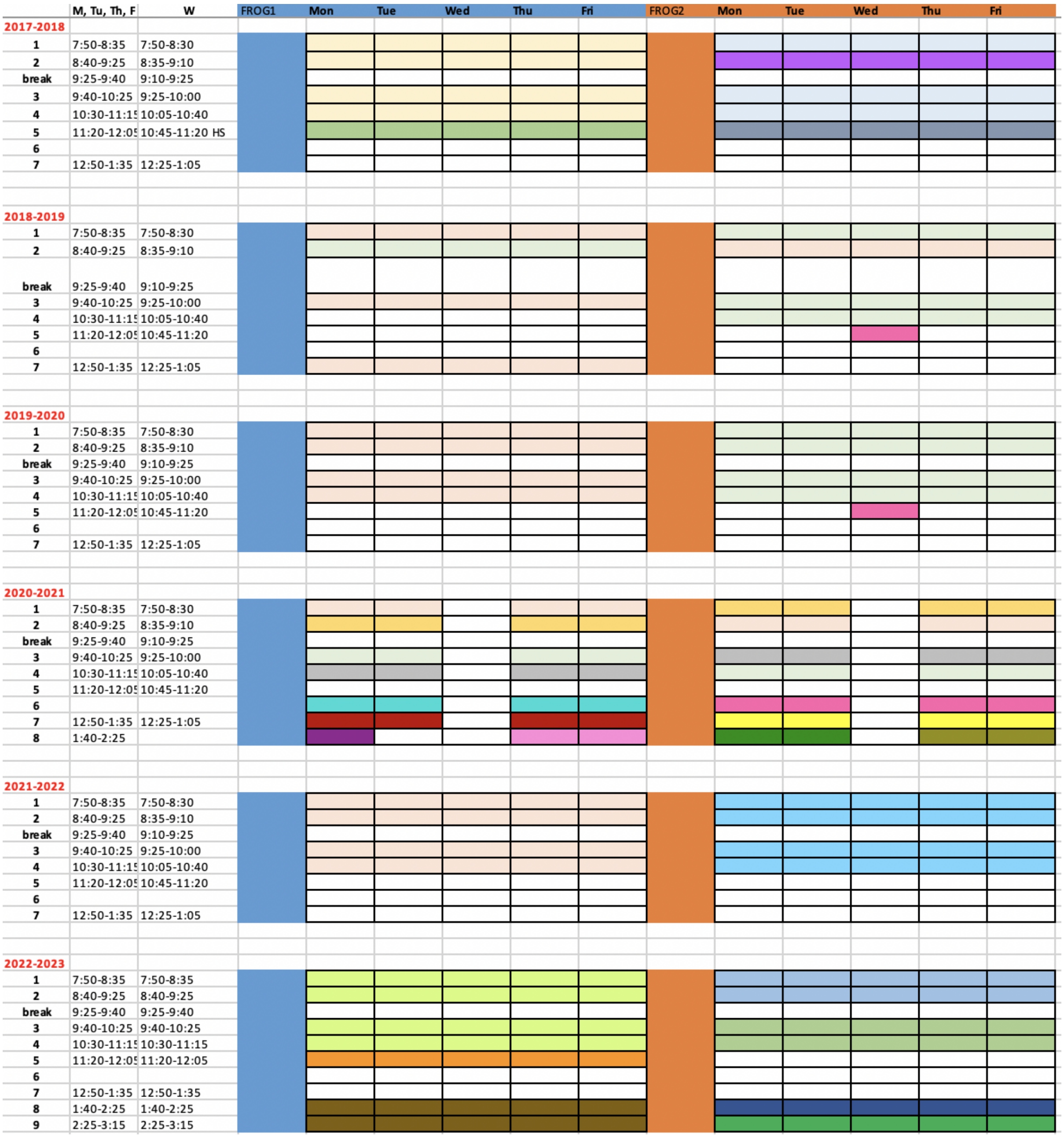
Table 1. *As-built characteristics of the UHM FROGs (134 m^2).*

Component	**Description**
Exterior wall	R-24 walls
Roof	R-30 roof decks
Glazing	Low-e, PPG Solarban 70XL glazing (SHGC=0.27; U=0.24; VLT=64%)
Lighting	Direct/Indirect LED lighting with daylight control
Ventilation	Mechanical exhaust 24.4 l/s (51.8 cfm)
Windows	High and low operable windows for natural ventilation located on the N and S side
Ceiling fans	Seven speed ceiling fans
Central AC	High efficiency split system fan coil and condensing unit (EER: 11.8)
Cooling set-point	25°C (77°F)
Renewable system	Solar PV systems: 8 kW per structure
Plug loads	Laptops, projector, computer servers, fire alarm, telecommunication, dashboard
Additional info	All electric, no natural gas on site

3.2 Classroom composition and scheduling

In addition to serving as research platforms, the FROGs were used as individual classrooms for University Lab School (ULS) middle school students in the morning and university students (UH students) in the afternoon and evening for the school years 2017-18 and 2018-19. In 2021, use of the classrooms became dedicated to the ULS. Traditionally, air conditioned buildings were operated in *change-over mode* where natural ventilation and HVAC operation are mutually exclusive. Because the windows and HVAC system are manually-controlled, they may also be run in a *concurrent mode*, when HVAC and natural ventilation occur simultaneously. The mode is chosen by user preference.

The classrooms were monitored over six calendar years (six school years: 2017-18; 2018-19; 2019-20; 2020-21; 2021-22; 2022-23) to collect disaggregated energy, indoor and outdoor parameters (Table 2). The buildings are occupied during the mornings (8:00 am–12:00 pm) from Monday to Friday by several groups of middle and high school students (45-min classes, 28 ULS students and 1 instructor; Figure 2). This type of scheduling with different user groups is not limited to educational buildings but can also reflect other types of end-uses with irregular occupancy such as offices, business incubators, or meeting rooms. The following analyses focused only on the morning sessions when the classrooms were used by ULS students.



	M, Tu, Th, F	W
2017-2018		
1	7:50-8:35	7:50-8:30
2	8:40-9:25	8:35-9:10
break	9:25-9:40	9:10-9:25
3	9:40-10:25	9:25-10:00
4	10:30-11:1	10:05-10:40
5	11:20-12:0	10:45-11:20 HS
6		
7	12:50-1:35	12:25-1:05
2018-2019		
1	7:50-8:35	7:50-8:30
2	8:40-9:25	8:35-9:10
break	9:25-9:40	9:10-9:25
3	9:40-10:25	9:25-10:00
4	10:30-11:1	10:05-10:40
5	11:20-12:0	10:45-11:20
6		
7	12:50-1:35	12:25-1:05
2019-2020		
1	7:50-8:35	7:50-8:30
2	8:40-9:25	8:35-9:10
break	9:25-9:40	9:10-9:25
3	9:40-10:25	9:25-10:00
4	10:30-11:1	10:05-10:40
5	11:20-12:0	10:45-11:20
6		
7	12:50-1:35	12:25-1:05
2020-2021		
1	7:50-8:35	7:50-8:30
2	8:40-9:25	8:35-9:10
break	9:25-9:40	9:10-9:25
3	9:40-10:25	9:25-10:00
4	10:30-11:1	10:05-10:40
5	11:20-12:0	10:45-11:20
6		
7	12:50-1:35	12:25-1:05
8	1:40-2:25	
2021-2022		
1	7:50-8:35	7:50-8:30
2	8:40-9:25	8:35-9:10
break	9:25-9:40	9:10-9:25
3	9:40-10:25	9:25-10:00
4	10:30-11:1	10:05-10:40
5	11:20-12:0	10:45-11:20
6		
7	12:50-1:35	12:25-1:05
2022-2023		
1	7:50-8:35	7:50-8:35
2	8:40-9:25	8:40-9:25
break	9:25-9:40	9:25-9:40
3	9:40-10:25	9:40-10:25
4	10:30-11:1	10:30-11:15
5	11:20-12:0	11:20-12:05
6		
7	12:50-1:35	12:50-1:35
8	1:40-2:25	1:40-2:25
9	2:25-3:15	2:25-3:15

Figure 2. *Scheduling comparison and occupancy capacity of UHM FROGs buildings.*

Over the course of the study the teaching environment and routines were consistent with no dramatic changes in operation in the first two school years. In the 2019-20 school year, August 9-March 13, 2019 (pre-COVID-19) FROGs were under normal operations. Following spring break 2020, the students did not return to campus due to the COVID-19 pandemic. In the 2020-21 school year, the students were not allowed on campus until March 25, 2021. For the 4th quarter, students were on campus, but the users of the FROG would have only been 14 students at a time on an A/B rotation-by-day schedule. In the 2021-22 school year, lessons were taught in person using the FROGs daily from August 9 to present, with 28 students in the classroom.

Data analyzed for this report are from August 2017, after commissioning was complete and regular classroom scheduling was implemented.

Initial training of ULS and UH instructors was provided by HNEI staff in 2017, and then again in spring 2019, aimed to foster a more conscious energy efficient behavior by allowing the building occupants to understand the building's features, including visualization of energy usage and PV generation through the dashboard installed in each building. During the training HNEI and ERDL personnel explained the operating protocols of the buildings, provided a wall poster to provide visual reminders to the occupants. The CO_2 sensors were also discussed to encourage natural ventilation using operable windows versus mechanical air conditioning. The latter is important because anecdotal evidence suggests that inadequate fresh air is being provided when staff elects to not open windows, either because of drafts or that they are unaware of the relationship to indoor air quality (Coley et al., 2002). Considering the current pandemic situation and the very recent results (Abuhegazy et al., 2020) of numerical simulation of aerosol transport in classroom environment it becomes of critical importance for COVID-19 mitigation to open windows even when the air conditioning is on and the classroom design has followed the ASHRAE 62.1 ventilation standard for acceptable indoor air quality. Opening windows while the air conditioning system is running, while traditionally not recommended from an HVAC or energy efficiency perspective, significantly increases particle exit fraction by ~38% and reduces transmission between students by ~80% [14].

3.3 Monitoring methods

Whole building net energy use in both buildings was monitored with eGauge meters beginning in September 2016. Data collection from indoor environmental sensors and sub-metering of major loads on the breaker panel began in January 2017. In January 2018, photovoltaic (PV) systems were installed on the rooftop of both buildings, and a weather station was installed on FROG 1, collecting ambient outdoor temperature, relative humidity, solar radiation, wind speed and direction every 5 min.

The indoor environmental parameters collected were temperature, relative humidity, light, and CO_2. The CO_2 sensor calibrates itself to 400 ppm based on the lowest reading that is stable (+/- 40 ppm) for 15 minutes every 24 hrs but the actual baseline concentration was recorded above that level. Average annual readings for CO_2 from the NOAA's Global Monitoring Laboratory on Mauna Loa, Hawai'i [26], were used as the baseline and all measured readings were calibrated so the lowest reading matched the NOAA reading for that year (Table 2).

Table 2. *Average ambient CO_2 concentrations (ppm) measured at the Global Monitoring Laboratory at Mauna Loa, Hawaiʻi.*

Calendar Year	Mauna Loa Average CO_2 reading (ppm)
2017	407
2018	409
2019	412
2020	414
2021	416
2022	417

Energy use was disaggregated the by following end-uses: air-conditioning compressor and fan coil unit; internal and external lighting; ceiling fans; whole building use; and solar PV systems. Power was monitored continuously with a PowerScout 24 power meter and averaged at a five-minute resolution with WebCTRL®software. Indoor temperature, relative humidity, illuminance, and CO_2 were monitored at a five-minute resolution. Energy and environmental data were collected through an Automated Logic LGR 50 controller module. WebCTRL® software automatically saved the data to a UH server. A third-party plugin for WebCTRL® was used to extract the data and transfer it to the database. Data was acquired over the internet and inserted into a database using Ionoa, a custom software developed by the UH School of Architecture's Environmental Research and Design Laboratory (ERDL; https://github.com/erdl/lonoa).

The following summarizes missing data due to equipment issues, (either monitoring or end-use) for all FROGs, FROG 1, and FROG 2:

- Missing all data: 3/18/2018-4/6/2018, 2/9/2021-3/10/2021;
- Missing FROG 1 data: 4/14/2017, 8/10/2018-8/17/2018, 4/8/2019, 5/16/2021-6/6/2021;
- Missing FROG 2 data: 11/14/2019-11/25/2019, 12/14/2020-12/16/2020 (missing CO_2 only), 4/12/2021 CO_2, 4/16/2021-5/5/2021, 5/10/2021-5/13/2021.

Due to the high number of missing data from FROG 2, only data from FROG 1 has been analyzed.

3.4 Outdoor climate in Mānoa Valley

The two FROGs buildings are located in the Mānoa (UHM) campus of the University of Hawai'i in the Lower Mānoa Valley, north-east inland from Waikiki. The valley receives almost daily rain, even during the dry season but the campus is located at the entrance to a valley, thus the weather is characterized by a tropical wet and dry savanna climate with a pronounced dry season (Köppen-Geiger climate classification "As" [15, 16] or in the International Energy Conservation Code (IECC) climate zone 1A, which is considered hot and humid [4]. The climate is divided in mainly two seasons: dry season (Apr.-Oct.) and wet season (Nov.-Mar.) (Figure 3).

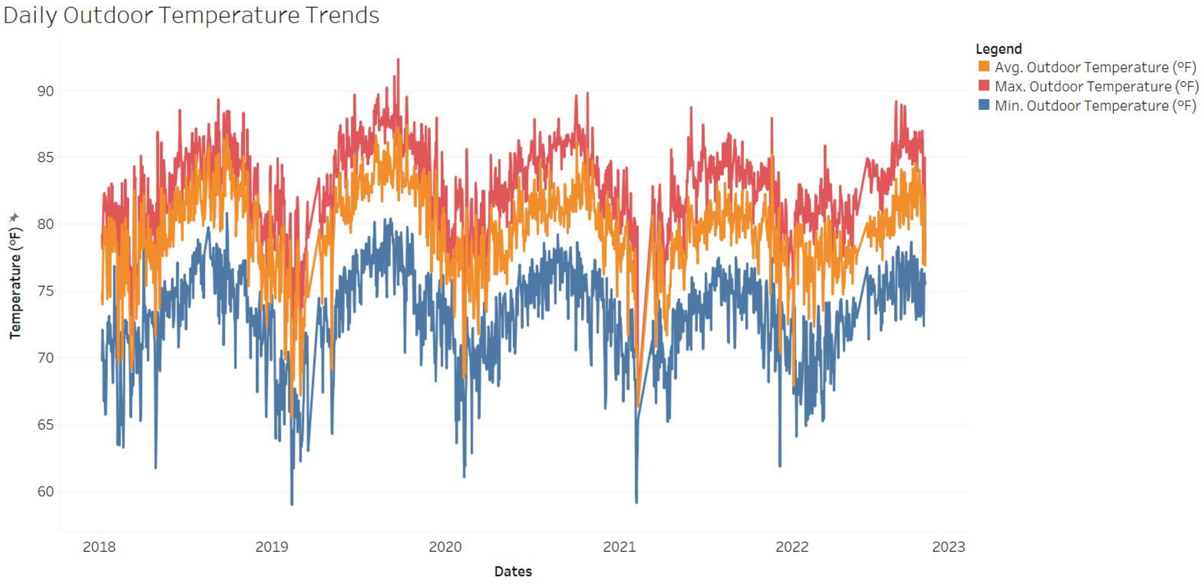


Figure 3. *Outdoor average, maximum, and minimum temperature conditions (°F).*

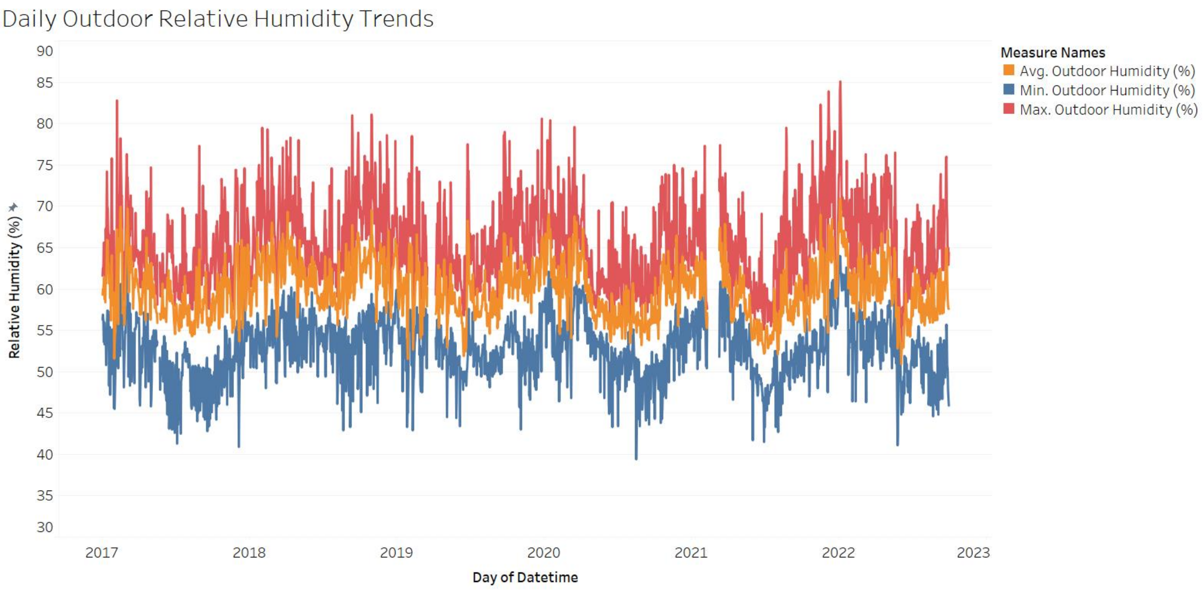


Figure 4. *Outdoor average, maximum, and minimum relative humidity conditions (%).*

The average monthly temperature is above 70°F for the entire measurement period, reaching values above 85°F during the dry season in 2018 and 2019 (Figure 3). Six calendar years of outdoor temperature data showed the average monthly temperature ranged from 70°F to about 85°F. Typically, the hottest days are from July to October, and the coolest days are from January to March.

The average monthly relative humidity (RH) ranged from 55% to 70% (Figure 4). Relative humidity is a very important parameter to look at especially in tropical climates The averaged values do not evidence a seasonal variation.

4 Results and Discussions

4.1 Energy – evaluations for the morning session (from 8:00 am to 12:00 pm) on Schooldays

Energy consumption is distributed among four primary end-uses: HVAC, ceiling fans, lighting and “other loads” that include telecommunications, fire-alarm, multimedia, and miscellaneous plug loads. During the monitored energy period (Aug. 2017-October 2022) there were intermittent technical issues with the monitoring system, thus a few days have been removed from the analyses (see Table 3). The HVAC in FROG 1 was not functional from Sept. 17 to Oct. 15, 2018 (29 days) and from Nov. 15, 2018 to May 15, 2019 (182 days). Figure 5 shows the energy used (kWh) by the building during the different quarters, evaluated over 4-hr periods.

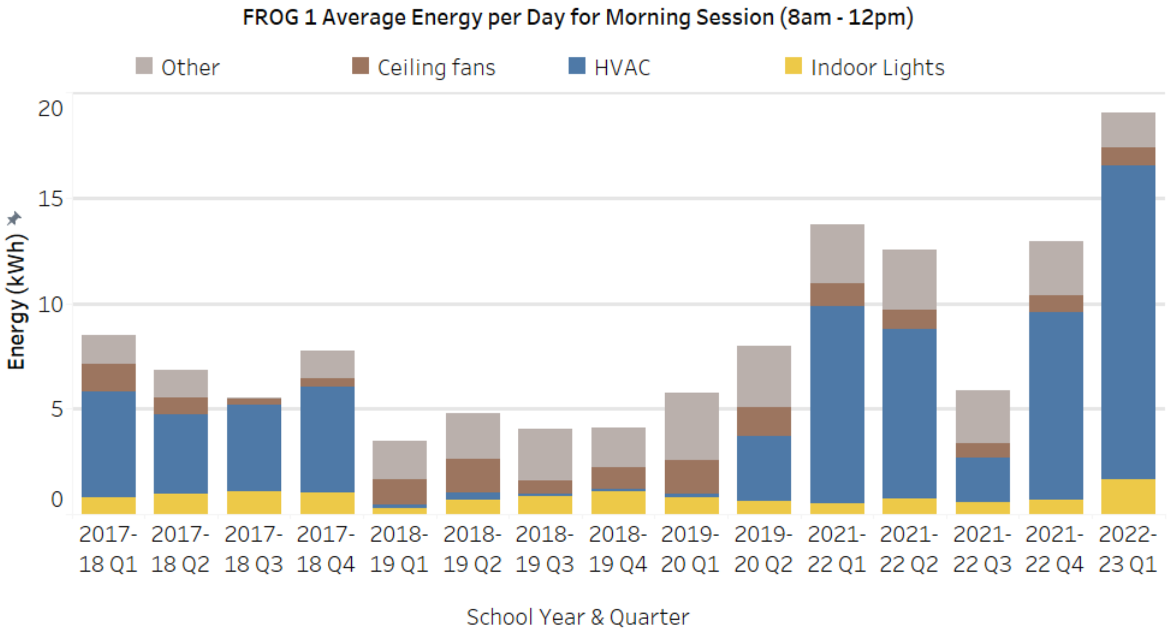


Figure 5. *UHM FROG 1 energy consumption (kWh) disaggregated by end use.*

Observations:

- The months of school year 2017-2018 Q3 (Jan.-Mar.) do not show values of the “other loads”. On January 2018 the PV system was installed on the roof but issues with the monitoring of the whole building data continued until mid-March 2018: the values of the HVAC, ceiling fan and indoor lights are correct but the other loads values were not included in the analyses.

- The building used more electricity for HVAC during the 2017-18 school year than in the following one. In the 2018-19 school year, FROG 1 was forced to operate in natural ventilation mode due to the HVAC system being out of commission. The downtime in the HVAC system can be seen in the lower average daily consumption of HVAC and the increase of the ceiling fan usage.

- From Q1 of school year 2021-22 the use of the HVAC system increased considerably. This was due to an increase in the fan speed setting for the air handling unit, and increased run time to improve ventilation and air exchange in response to the students returning to campus during the later stages of the COVID-19 pandemic.

As previously stated, users of FROG buildings attended training about how to operate the buildings in 2019. Previous studies [2, 10] of energy efficient buildings, such as the FROGs, have encouraged green practices and behaviors. Heerwagen and Diamond examined the three types of behavior adaptation (personal adjustments, technological or environmental adjustments, and psychological adjustments) in energy efficient buildings [17]. The researchers found that personal adjustments were made more than technological ones (i.e., windows, blinds, HVAC control, ceiling fans) in spaces which occupants have limited access to the control systems such as the open plan space. Azizi et al refer to the coping mechanisms occupants use in response to discomfort [10]. In fact, other studies show that when occupants are provided with access to the environmental control systems, they will be more likely to make adjustments that will impact energy usage in buildings [17, 18]. This is what happened in FROGs during the 2017-18 school year. However, O'Brien and Gunay raised concern that contextual factors such as occupants' awareness and perception of working in an energy efficient building can influence their choice of adaptive behavior [19]. For instance, occupants have been found to sometimes adopt poor energy saving behaviors in energy efficient design buildings due to the 'rebound effect' where, due to the perception of energy efficiency "savings" other end-use behaviors were relaxed and energy consumption increased [20, 21].

Table 3. *Details of the number of schooldays in the selected ULS quarters.*

School Year	Q1	Q2	Q3	Q4
2017-18	44	45	47	42
2018-19	42	43	41	33
2019-20	39	46	non occupied / COVID-19	non occupied / COVID-19
2020-21	non occupied / COVID-19	non occupied / COVID-19	non occupied / COVID-19	non occupied / COVID-19
2021-22	42	36	46	38
2022-23	37	N/A		

4.2 Indoor conditions - Schooldays only

The current study analyzed the indoor climate of UHM FROG 1 considering CO_2 (Figure 6) and the thermal outdoor and indoor conditions (Figure 7, Figure 8). Outdoor minimum CO_2 levels in Hawaiʻi ranged from 407 to 417 ppm (Table 2) during the study period. According to ASHRAE [22]. "Many countries have mandatory or suggested values for indoor CO_2 for non-industrial spaces. It should be noted that the rationale for these guideline values are not generally provided along with these guideline values. These indoor CO_2 limits tend to be on the order of 1,000 ppm_v[1] but range as high as about 1,500 ppm_v." Steinemann et al. investigated the concern that energy efficient buildings, called green buildings in the paper, may promote energy efficiency and other aspects of sustainability, but not necessarily the health and well-being of occupants through better indoor air quality [23]. Their study highlighted that IAQ in energy efficient buildings was mainly accessed using post-occupancy surveys, and they were collecting perceived air quality. Only in a few studies, the actual measurements of IAQ were carried out by documenting the levels of CO_2 or other pollutants and measuring the ventilation rates.

Figure 6, using school quarters with numbers of CO_2 measurements (average 5-minute interval values) that exceeded 700 ppm shows a higher number of CO_2 values exceeding 700 ppm, 1,000 ppm and reaching 2,000 ppm, during the morning sessions for all quarters of the school year 2017-18. Given that due to limits of the range of the instruments, the maximum measurable CO_2 value of the sensor

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[1] v is for volume. Most ppm is based on weight (e.g. mg/kg), but this is in gas form.

is 2,000 ppm[2], implying that the real CO_2 values experienced in the building during the morning lessons exceeded that upper measurement threshold. This has negative implications for the health and learning outcomes of the students [7, 24, 25].

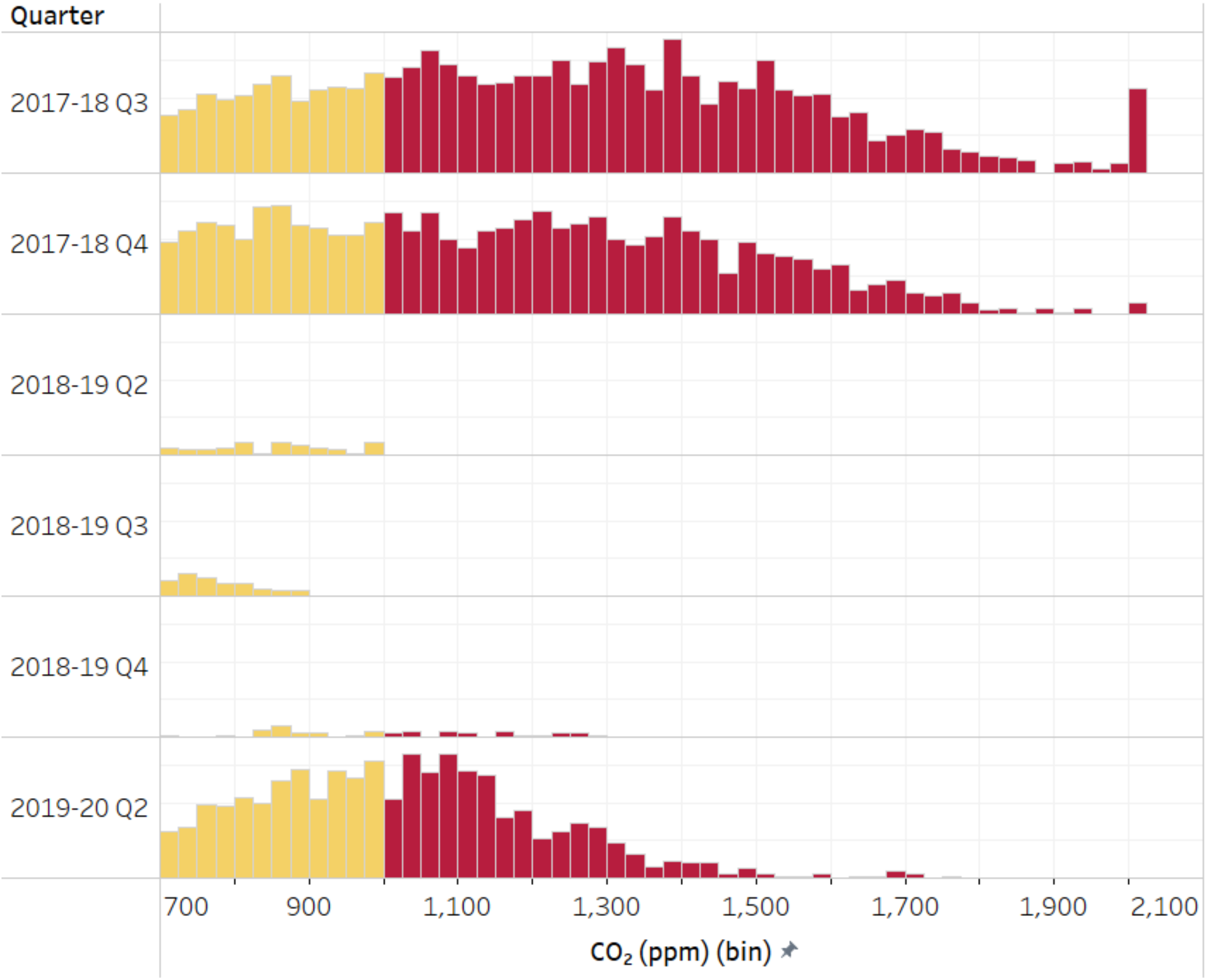

Figure 6. *Quarters when number of CO_2 values exceeded 700 ppm (yellow) and 1,000 ppm (red) – on schooldays morning sessions (8 am to 12 pm) only.*

During the following school year (2018-19), occupants used natural ventilation because the HVAC was out of commission from 9/17/18 to 10/16/18 and again from 11/15/18 to 5/16/19 and this strategy improved the indoor air quality. Interestingly, during the following school year 2019-20 the HVAC was again down from 8/27/19 to 10/31/19. After being repaired, users began to use the rooms without opening doors and windows to ventilate the building. The CO_2 rose to 1,700 ppm during Q2. The COVID-19 pandemic increased ventilation awareness causing users to use the operable windows to ventilate the building, with CO_2 values dropping during Q3 to below 700 ppm.

The outdoor and indoor conditions (temperature and relative humidity) were evaluated by quarters. The average outdoor temperatures were higher when HVAC was out of service (Q1-Q4 2018-19; Q1 2019-20) yet the average indoor relative humidity values stayed below 70% independently of HVAC

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[2] The CO_2 sensor was a non-dispersive infrared type manufactured by AutomatedLogic, model ZS-HC-ALC, with an accuracy for the range 400 ppm to 1,250 ppm of +/-30 ppm or 3% of reading (whichever is greater) and for the range 1,250 ppm to 2,000 ppm an accuracy of +/- 5% of reading plus 30 ppm.

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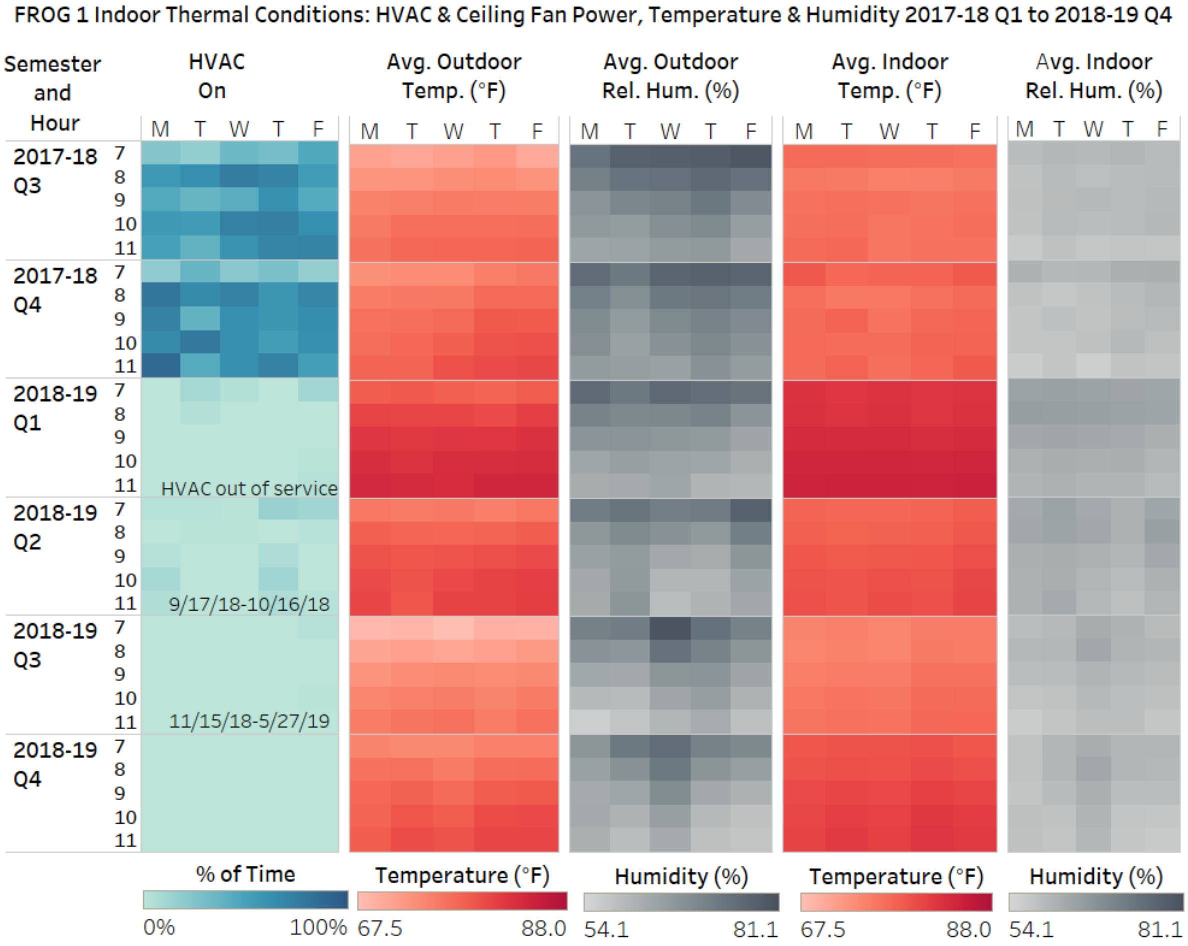


Figure 7. *Thermal indoor and outdoor conditions by quarter (2017-18 Q1 to 2018-19 Q4) for schoolday mornings.*

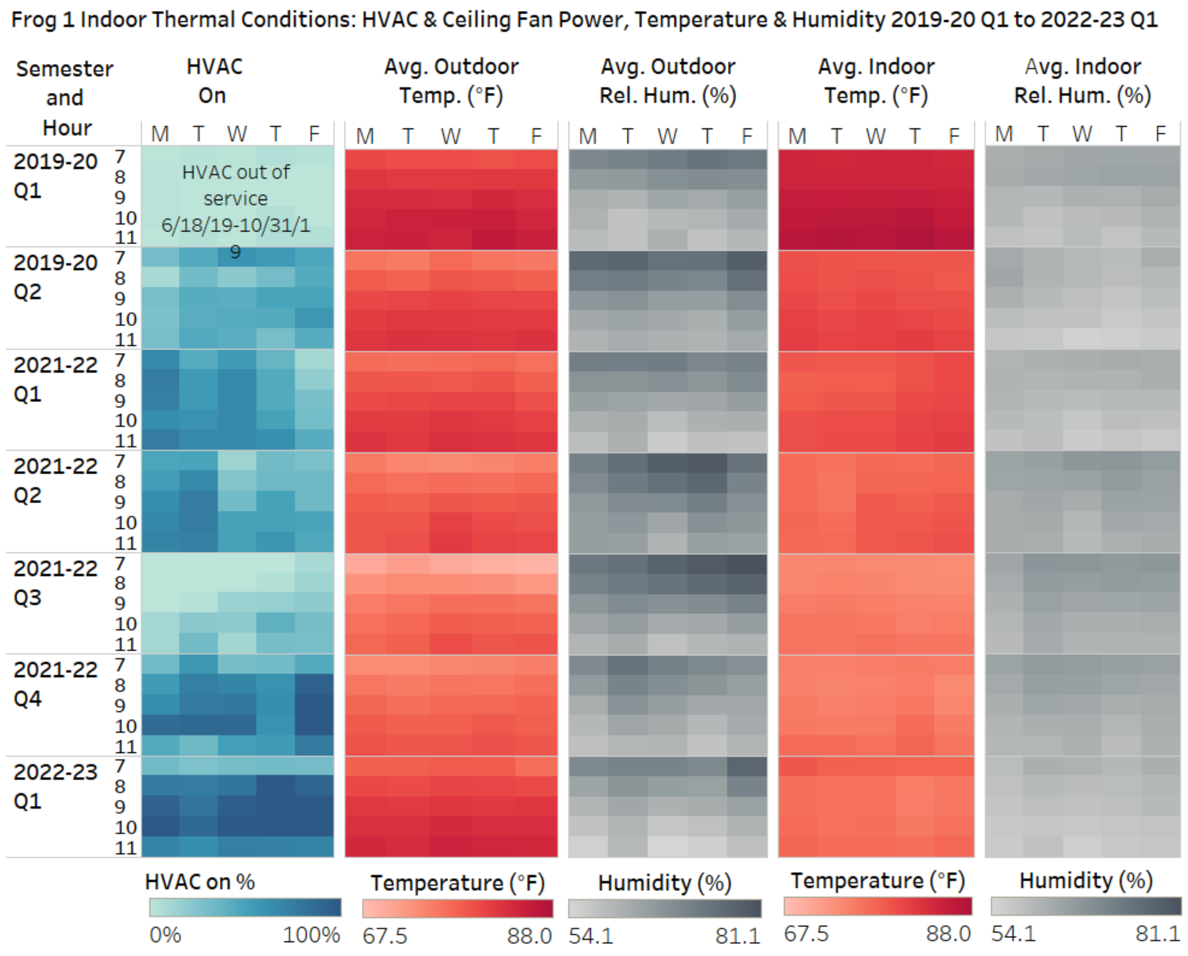


***Figure 8.** Thermal indoor and outdoor conditions by quarter (2019-20 Q1 to 2022-23 Q1) for schoolday mornings.*

4.2.1 Average hourly CO_2 averages - Morning sessions only - Schooldays only

The following heat maps in Figure 9-Figure 21 show the average hourly CO_2 values from 6 am to 12 pm during the different quarters.

The heat maps have two visual indicators: the size of the squares and the colors, both ranging from the minimum value of 430 ppm to 2,035 ppm (four equal CO_2 steps: 430-831 ppm; 831-1,232 ppm; 1,232-1,634 ppm; 1,634-2,035 ppm). The color does not change inside the CO_2 step, but the size does, and provides additional information.

The building used more HVAC than ceiling fans during the 2017-18 school calendar year (Figure 9-Figure 12) and shows also very high hourly CO_2 values. Often early morning values (between 6:00 am and 6:59 am) are higher than the baseline. Figure 13-Figure 17 show stable CO_2 levels that generally remain below 1,000 ppm from August 2018 to October 2019. Values began to rise again just prior to the pandemic (Figure 18), then due to the recommendations provided by WHO, such as increasing ventilation in buildings, values dropped to the first CO_2 step (430-831 ppm).

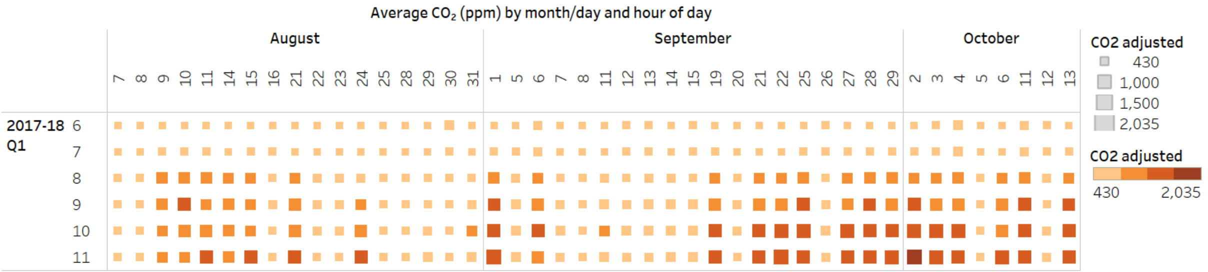


Figure 9*. FROG 1: heat map of the average indoor CO₂ values during Q1-ULS 2017-18 (Aug. 7-Oct. 13, 2017); 6 am-12 pm; Schooldays only.*

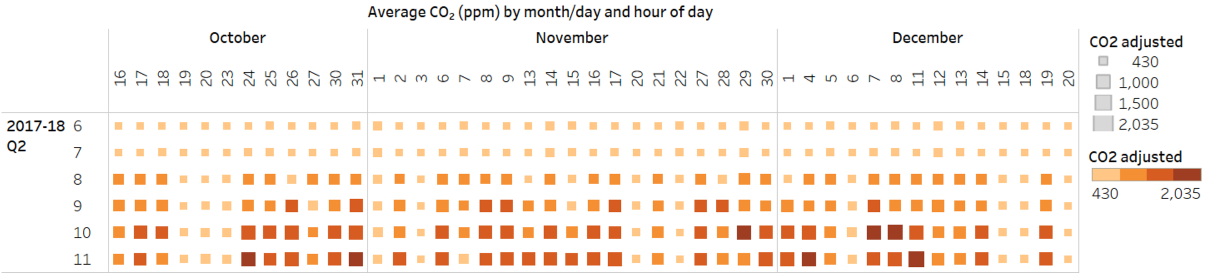


Figure 10. *FROG 1: heat map of the average indoor CO₂ values during Q2-ULS 2017-18 (Oct. 16-Dec. 20, 2017); 6 am-12 pm; Schooldays only.*

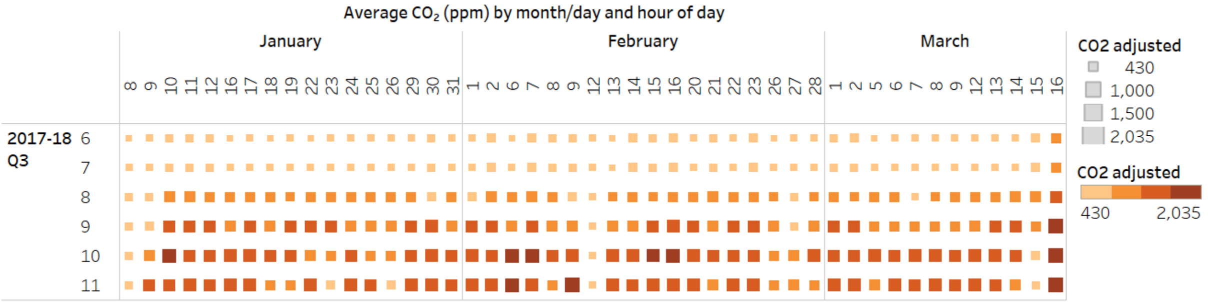


Figure 11. *FROG 1: heat map of the average indoor CO₂ values during Q3-ULS 2017-18 (Jan. 8-Mar. 16, 2018); 6 am-12 pm; Schooldays only.*

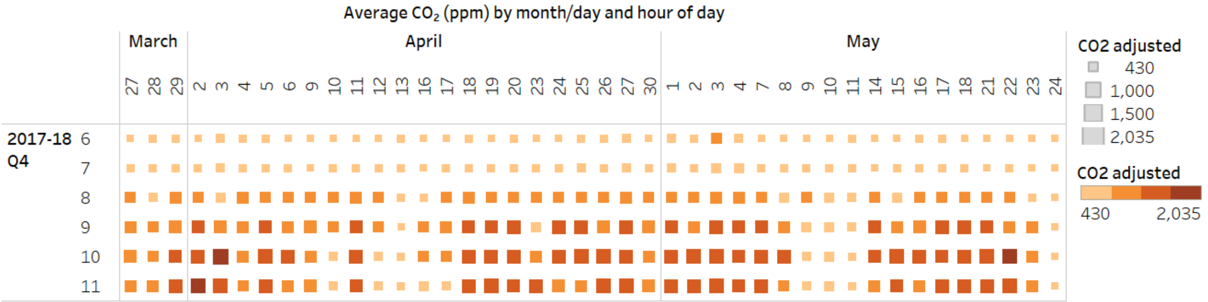


Figure 12. *FROG 1: heat map of the average indoor CO₂ values during Q4-ULS 2017-18 (Mar. 27-May 24, 2018); 6 am-12 pm; Schooldays only.*

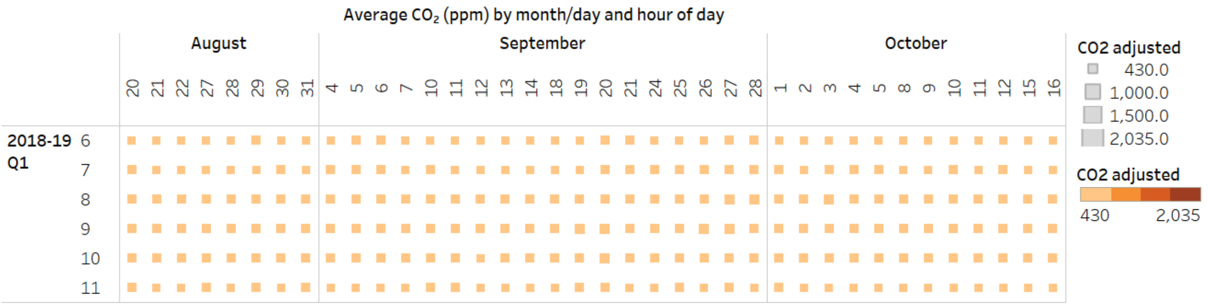


Figure 13. *FROG 1: heat map of the average indoor CO₂ values during Q1-ULS 2018-19 (Aug. 20-Oct. 16, 2018); 6 am-12 pm; Schooldays only.*

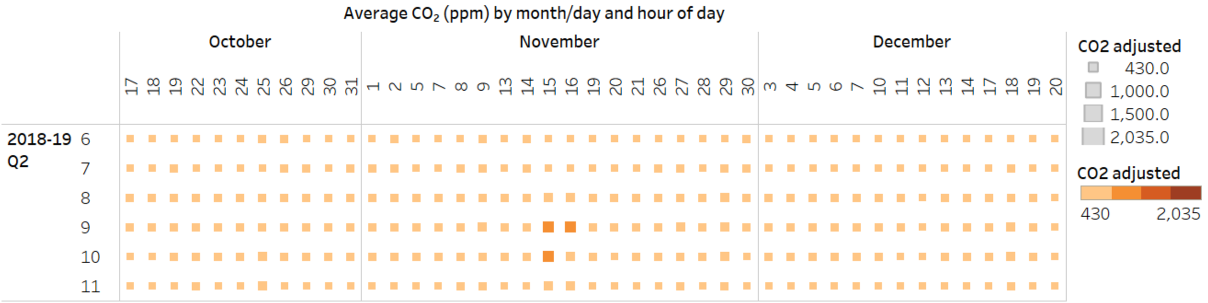


Figure 14. *FROG 1: heat map of the average indoor CO₂ values during Q2-ULS 2018-19 (Oct.17-Dec.20, 2018); 6 am-12 pm; Schooldays only.*

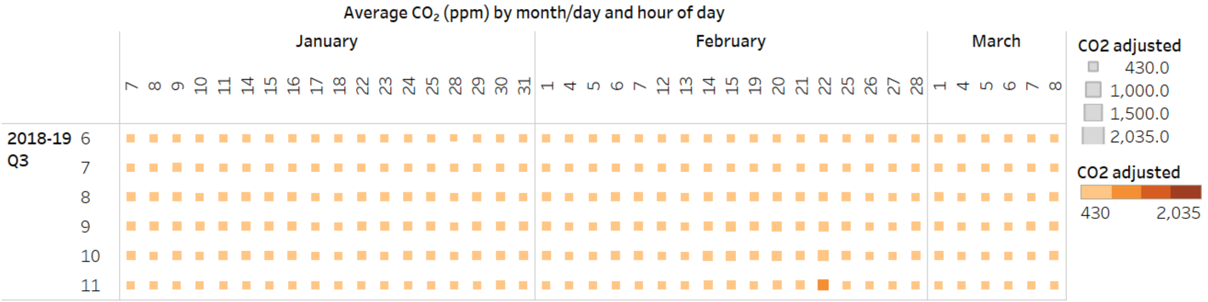


Figure 15. *FROG 1: heat map of the average indoor CO₂ values during Q3-ULS 2018-19 (Jan. 7-Mar. 8, 2019); 6 am-12 pm; Schooldays only.*

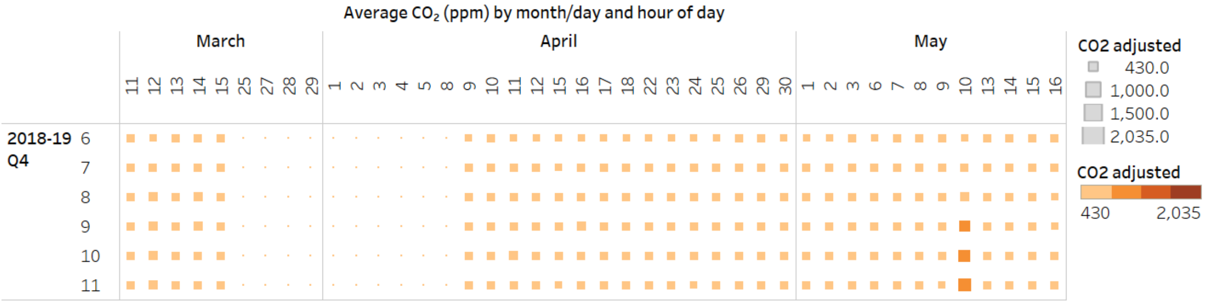


Figure 16. *FROG 1: heat map of the average indoor CO₂ values during Q4-ULS 2018-19 (Mar. 11-May 16, 2019); 6 am-12 pm; Schooldays only.*

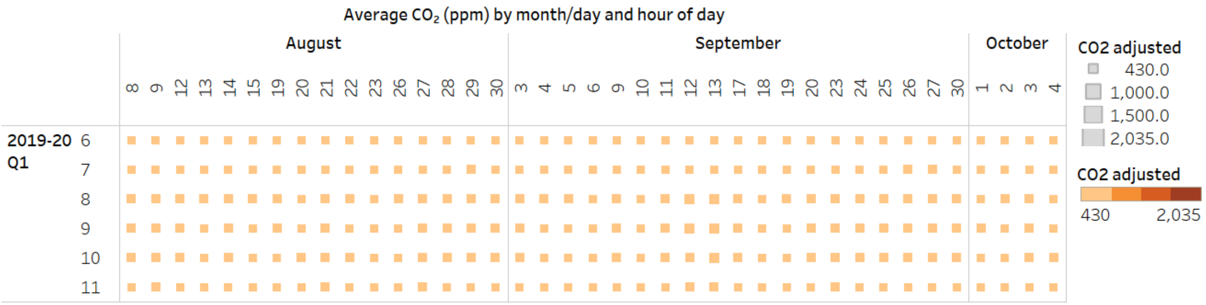


***Figure 17**. FROG 1: heat map of the average indoor CO₂ values during Q1-ULS 2019-20 (Aug. 8-Oct. 4, 2019); 6 am-12 pm; Schooldays only.*

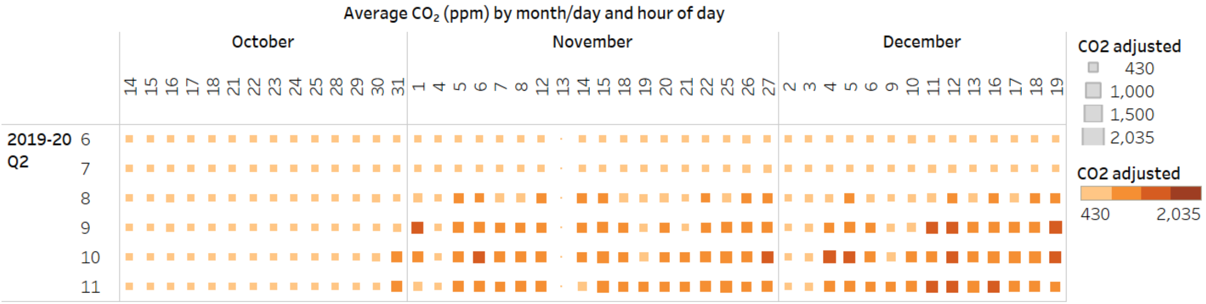


***Figure 18.** FROG 1: heat map of the average indoor CO₂ values during Q2-ULS 2019-20 (Oct. 14-Dec. 19, 2019); 6 am-12 pm; Schooldays only.*

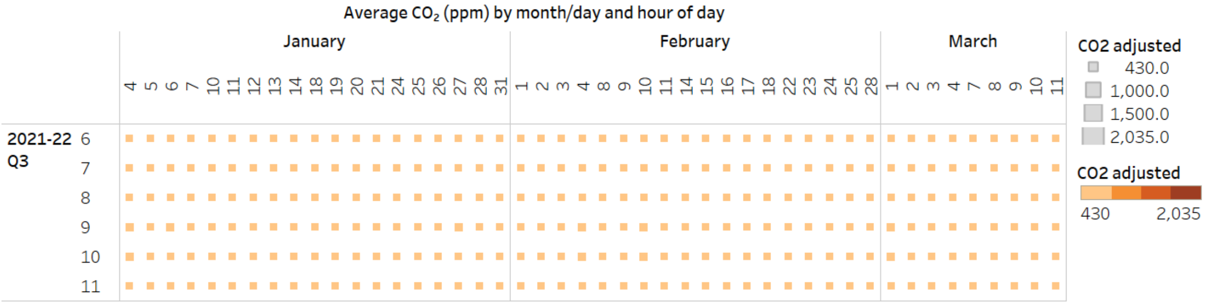


***Figure 19.** FROG 1: heat map of the average indoor CO₂ values during Q3-ULS 2021-22 (Jan. 4-Mar. 11, 2022); 6 am-12 pm; Schooldays only.*

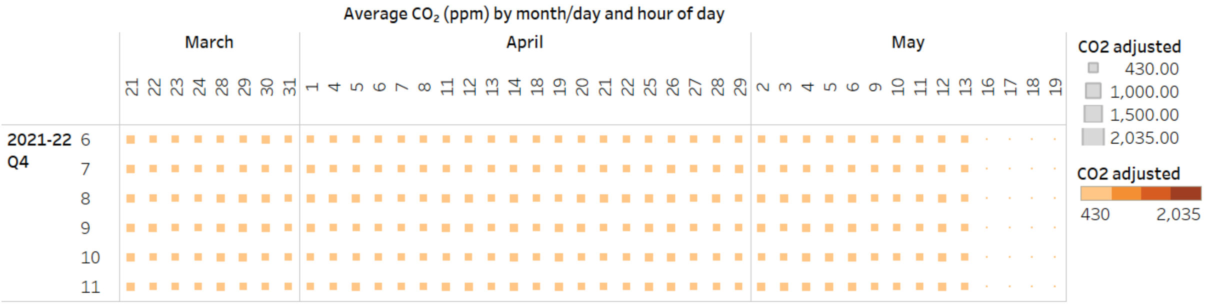


***Figure 20.** FROG 1: heat map of the average indoor CO₂ values during Q4-ULS 2021-22 (Mar. 21-May 19, 2022); 6 am-12 pm; Schooldays only.*

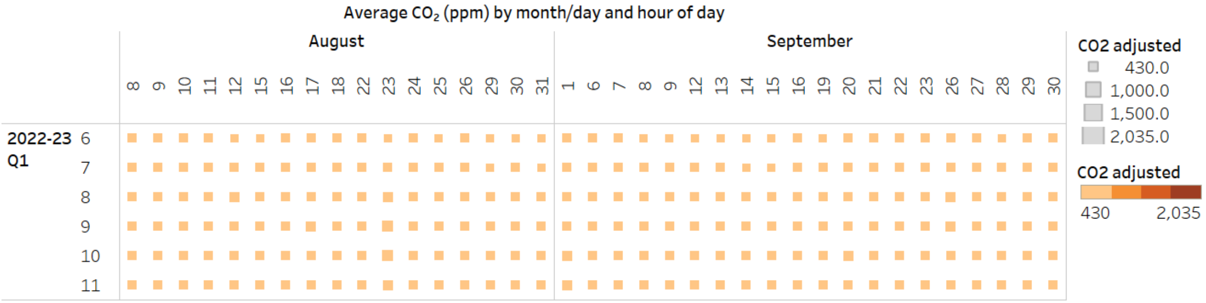


Figure 21. *FROG 1: heat map of the average indoor CO_2 values during Q1-ULS 2022-23 (Aug. 8-Sep. 30, 2022); 6 am-12 pm; Schooldays only.*

4.3 Rate of CO_2 dissipation on selected days

The CO_2 concentration dissipation rate was studied to determine the natural diffusion of CO2 over a period when doors and windows were closed. A few days in 2019 were selected when sensors were able to record when windows were open. The average CO_2 values shown in the previous charts suggest that during the first investigated school year (2017-18) the morning CO_2 values may have started already high from the night before when windows were closed (Figure 9 - Figure 12). On Nov. 14, Nov. 25 and Dec. 9, 2019, the CO_2 concentration rose above 1,000 ppm (Figure 22) when the building was occupied during mornings and afternoons. At night the windows remained closed. In all three cases, the CO_2 level at night remained higher than the fresh air baseline of 412 ppm for 2019 (based on Mauna Loa readings – Table 2). The CO_2 dissipation rate from 9 pm to 6 am for those nights ranged from 20 to 26 ppm/hr (Table 4). The conclusion was that the FROG building was constructed so tightly that exfiltration through window and door cracks did not fully dissipate gases and other indoor air pollutants, having a direct impact on the indoor air quality and safety of building's occupants, particularly in a pandemic situation.

When values higher than 800 ppm are reached at the end of the day, the building will took at least 15 to 16 hrs to reach 412 ppm with the windows closed. This implies that when the building is occupied later during the day, the CO_2 concentration of the next day is initially high when the classroom opens up for the day.

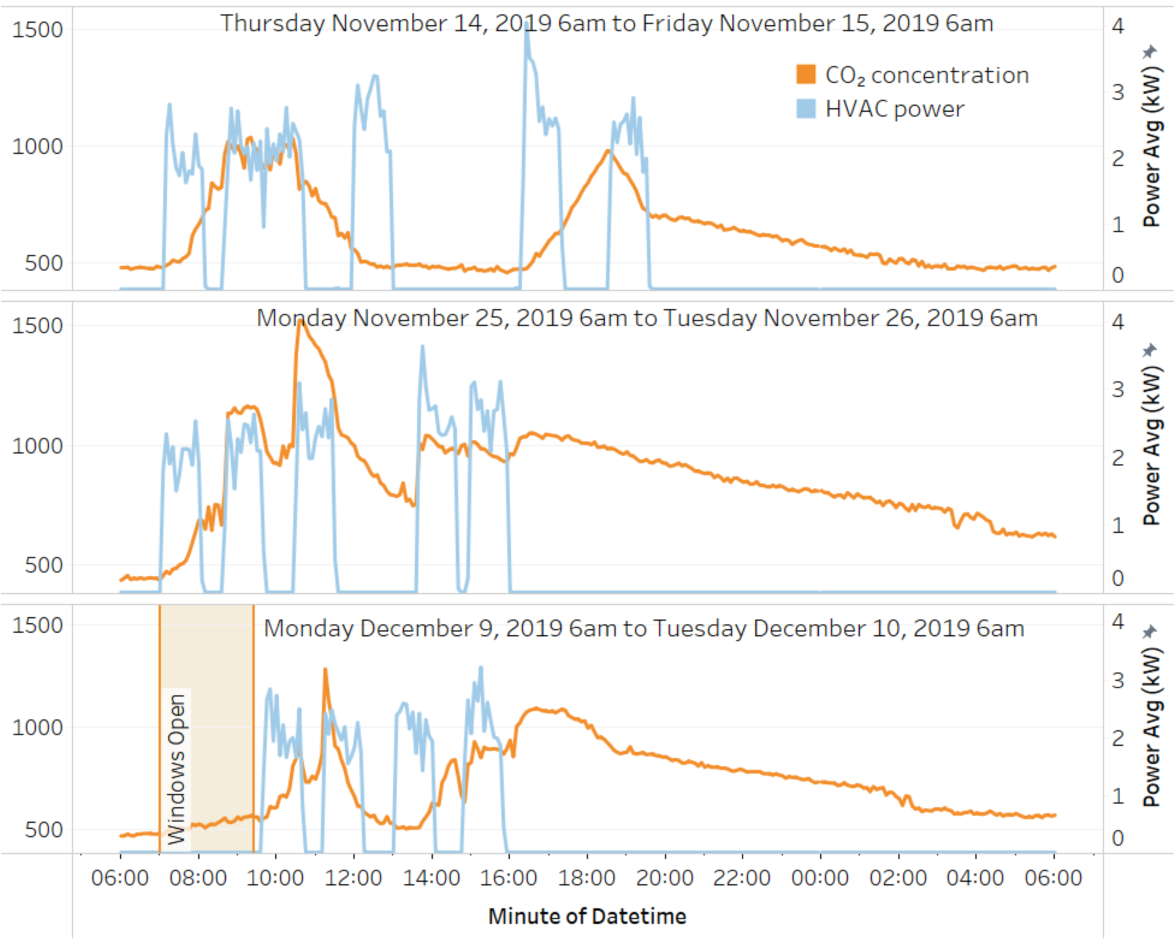


Figure 22. *Dissipation of CO_2 concentration overnight with windows closed, over 3 selected days with different use profiles.*

Table 4. *Dissipation of CO_2 concentrations overnight with windows closed.*

Start date/time	End date/time	Hours	Start ppm	End ppm	Dissipation rate (ppm/hr)	Estimated additional hrs to reach 412 ppm
11/14/2019 9:00 pm	11/15/2019 6:00 am	9	666	483	20.3	3.5
11/25/2019 9:00 pm	11/26/2019 6:00 am	9	881	617	29.3	7.0
12/9/2019 9:00 pm	12/10/2019 6:00 am	9	803	568	26.1	6.0

4.4 Impact of on-demand HVAC set up on energy

This section summarizes the HVAC energy usage data with the objective of understanding the impact the on-demand HVAC settings have on energy consumption. This analysis focused on the HVAC system because 1) it is the most energy intensive system of the building (it is important to estimate the potential savings due to the on-demand thermostat); 2) it affects the indoor air quality by controlling the amount of fresh air introduced into the building.

Figure 23 shows the HVAC power usage (kW) by on-demand settings over the investigated period. The data show the values over 24 hr periods of time and did not filter out the dates when the HVAC was broken (see data for 2019 as an example). The majority of the data for the 1-hr on-demand setting was obtained from 2017 to April 5, 2021. In April of 2021 the setting was then changed to an 8-hr run time (from April 5, 2021 to December 12, 2021) in order to increase ventilation and maximize the amount of outside fresh air that was being introduced into the classroom. In December of 2021, it was determined that the classrooms were not being used in full 8-hr blocks, and that a 4-hr setting would be sufficient. The on-demand setting has been 4 hours from December 12, 2021 through the October 2022 data collection period.

The same day the HVAC setting changed from 1-hr to 8-hr, the air handler fan speed was also increased to introduce more fresh air into the classrooms. This led to an increase in the air handler power use. Figure 24 shows that the average power demand changed from 2.4 kW and 0.4 kW for the compressor and air handling units to 3 kW and 0.70 to 0.75 kW, respectively, after the fan speed was increased.

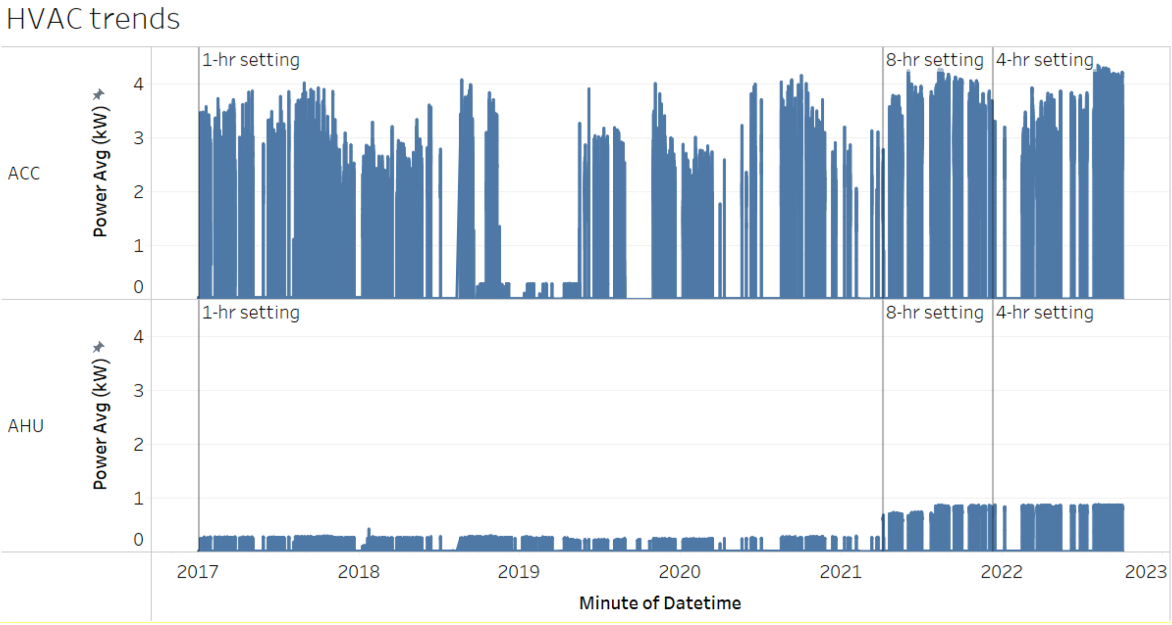


***Figure 23.** HVAC power demand (kW) and "on-demand" HVAC settings over the investigated period.*

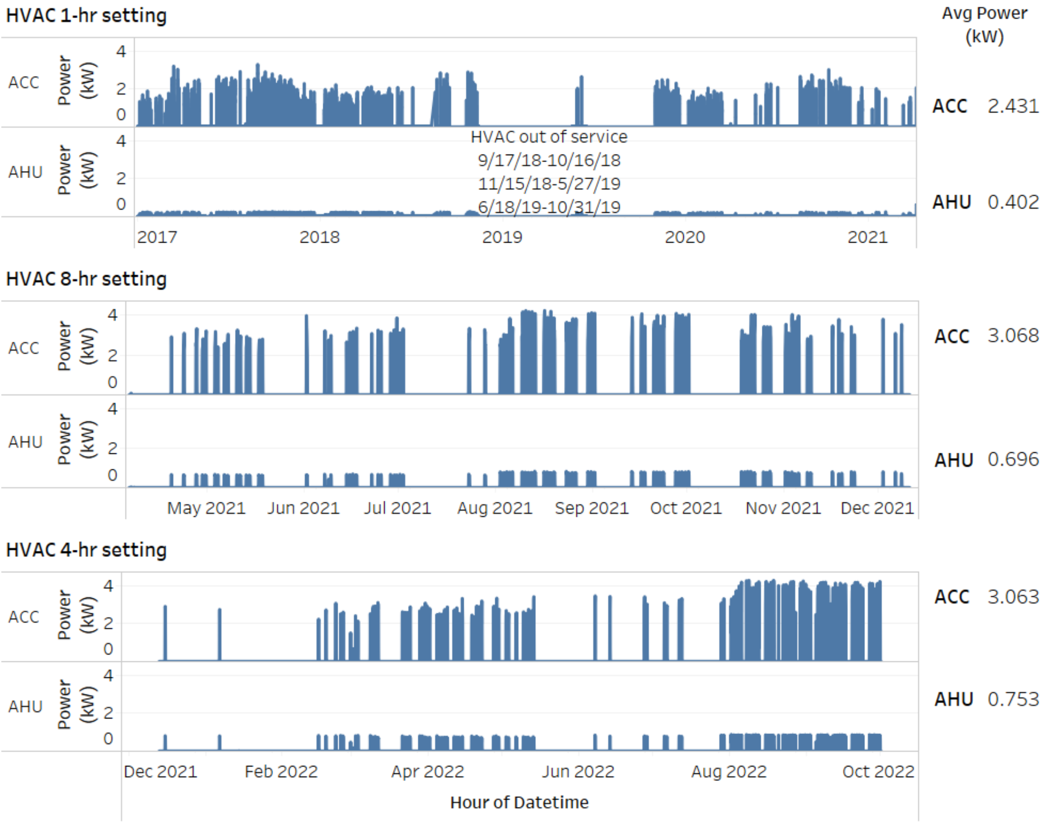


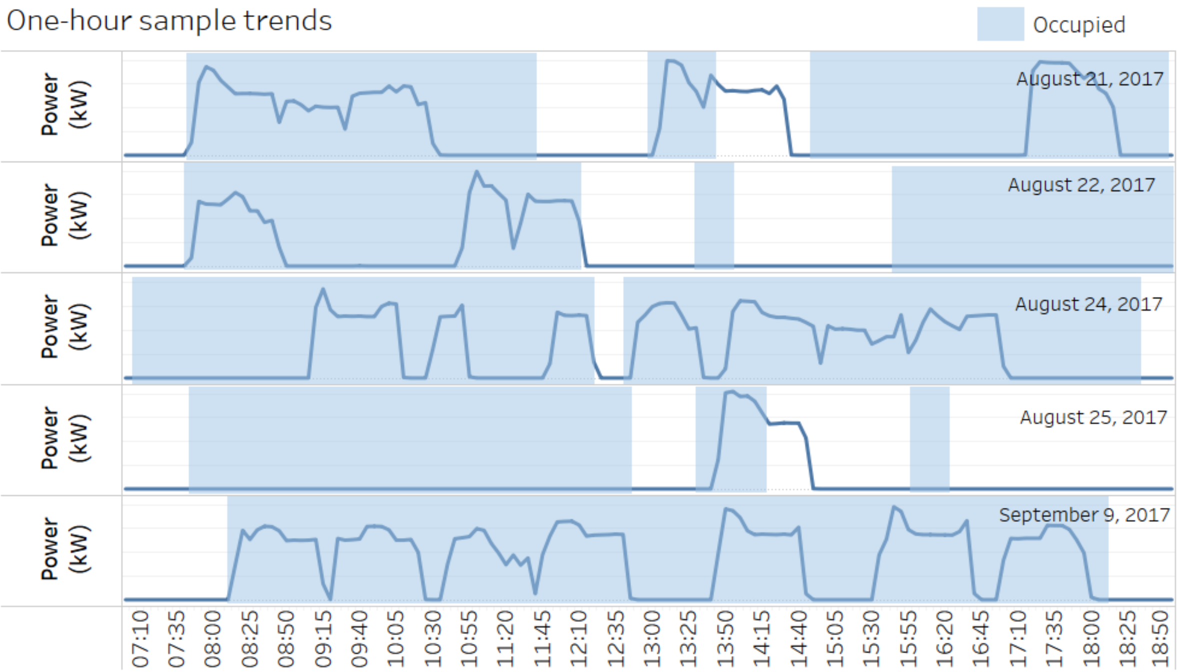
Figure 24. *Power demand (kW) of HVAC for each "on-demand" setting (not filtered for schooldays; days the HVAC was not functioning have been filtered out).*

The following charts (Figure 25-Figure 27) represent some examples of typical HVAC usage from 7 am to 7 pm, thus for a 12-hour period.

Figure 25 shows how diversified the HVAC usage can be during a typical schoolday (August 21-August 25, 2017). In 2017, when the building was used by ULS students during mornings and by University of Hawaiʻi students during afternoons and evenings, there are cases when HVAC was almost continuously running for 3 hours (August 21, 8 am-11 am; August 24, 2 pm-5 pm), but also cases where it was stopped before reaching 1-hr operation (August 24, 10:30 am, 11:45 am).

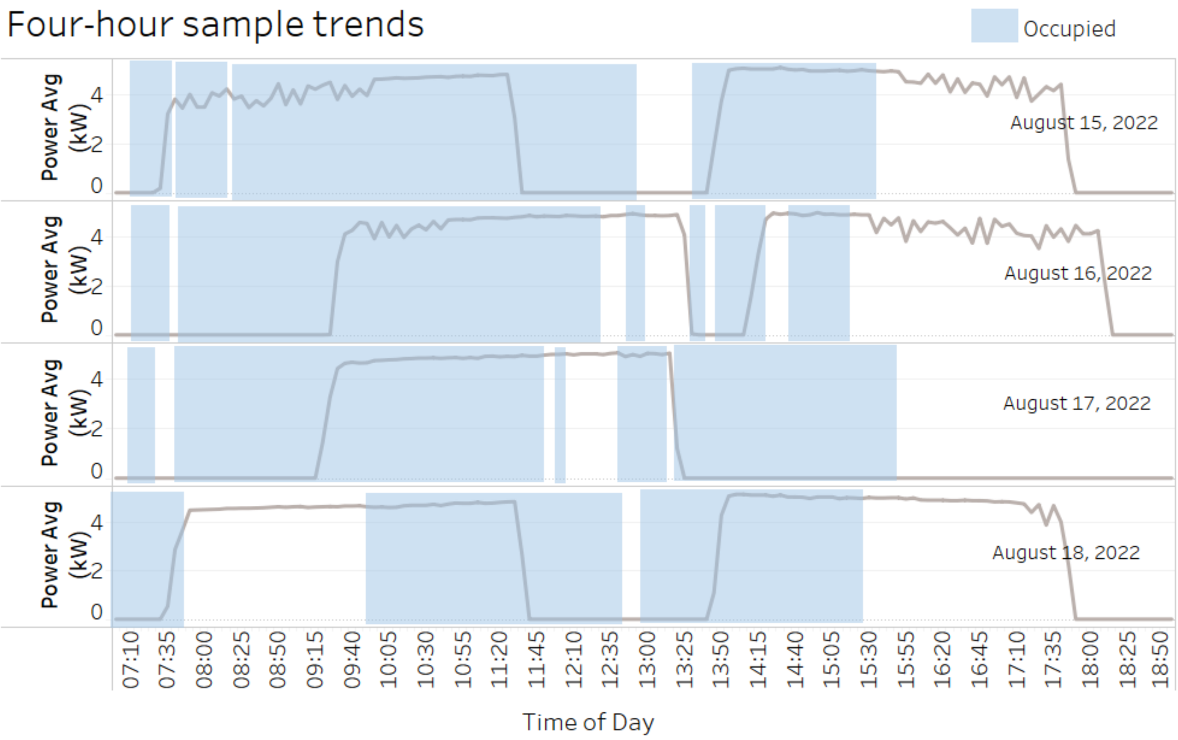
In the case of a 4-hour operation, Figure 26, on average the HVAC was used twice a day, during mornings and afternoons. Generally, the building was occupied up to about 3:00 pm and HVAC energy used after that time is considered "wasted". In this case, the HVAC usually shut off by 5:00 pm, with approximately 2 hours of wasted energy. With the 8-hr setting (Figure 27), energy was wasted when the HVAC was activated later in the day, such as on August 19, 2021 at which time the HVAC was turned on at about 11:30 am and remained running up to 7:30 pm, several hours after people have already left the building (approximately 3:00-5:000pm).

The charts in Figures 25-27 show also that periodically the HVAC ran for a lower or higher or number of hours. This reflects the decision of the user to either shut the HVAC down early on or immediately turned it on at the end of the run time.



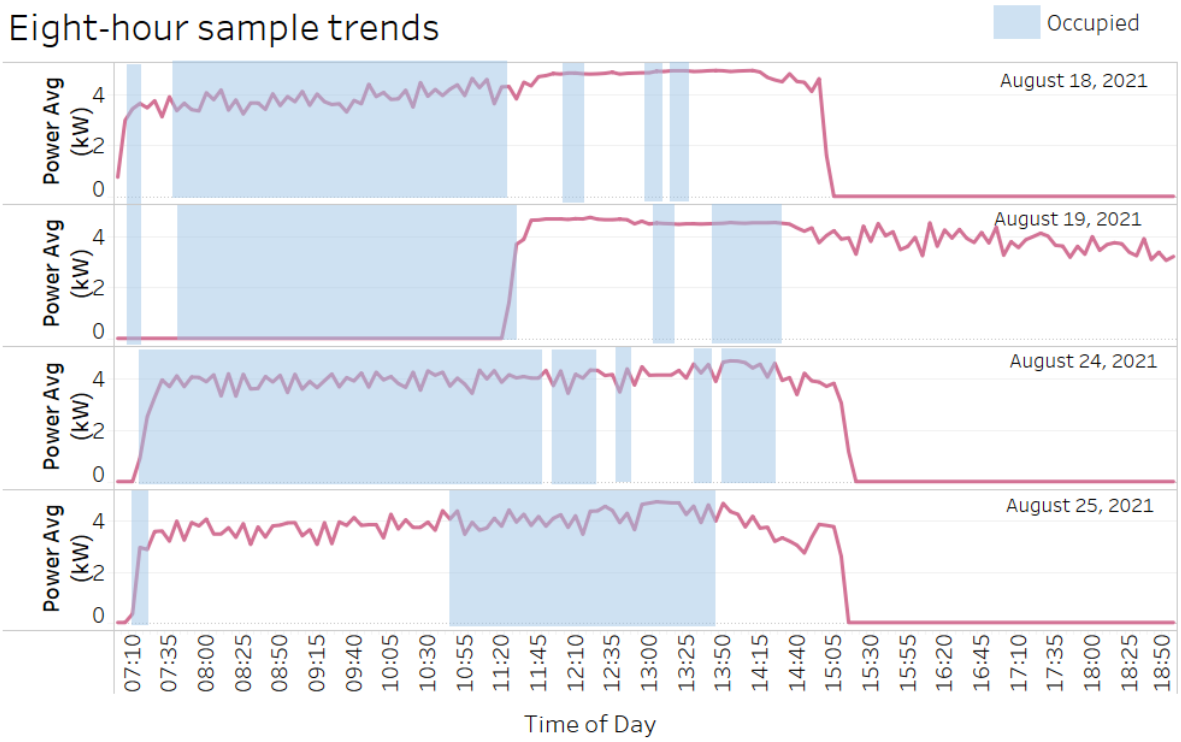
Dates	Hours/Day	Avg Power (kW)	Energy Use (kWh)
August 21, 2017	5.08	2.88	13.73
August 22, 2017	2.33	2.43	5.73
August 24, 2017	5.83	2.27	13.27
August 25, 2017	1.00	3.09	3.09
September 9, 2017	7.08	2.57	17.94

Figure 25. *One-hour sample trends (August 2017-schooldays only; September 9-Saturday).*



	Energy Use (kWh)	Hours/Day	Avg Power (kW)
August 15, 2022	34.84	8.00	4.35
August 16, 2022	35.55	8.00	4.44
August 17, 2022	18.89	4.00	4.72
August 18, 2022	36.92	8.00	4.61

Figure 26. *Four-hour sample trends (August 2022).*



	Energy Use (kWh)	Hours/Day	Avg Power (kW)
August 18, 2021	33.38	8.00	4.17
August 19, 2021	32.22	8.00	4.03
August 24, 2021	31.53	8.00	3.94
August 25, 2021	30.81	8.00	3.85

Figure 27. *Eight-hour sample trends (August 2021).*

The following table, Table 5, show the percentage of time HVAC was used when the building was occupied and the percentage of time HVAC was used when the building was unoccupied. With the 1-hr on-demand setting, occupants used the HVAC system 28% of the time. When set at 4 hours, the HVAC was on 37% of the time and 54% for the 8-hr setting. The on-demand control is intended to reduce HVAC energy use when the classroom is unoccupied. The HVAC system ran only 9% of time when unoccupied at the 1-hr setting. With on-demand set to an 8-hr setting, the HVAC ran 41% of unoccupied hours. On August 19, 2021, as shown in Figure 27, illustrates how excess energy is consumed if the HVAC is activated toward the end of the day and continues to run after the room is unoccupied. With the 4-hr setting, the HVAC ran 30% of unoccupied hours. As logic would dictate, shorter on-demand settings reduce energy waste significantly.

Table 5. *Percentage of time HVAC on when occupied or unoccupied (data have been filtered out when HVAC was broken).*

"On-demand" HVAC setting	**Percent of Time HVAC on When Occupied**	**Percent of Time HVAC on When Unoccupied**
1-hr	28%	9%
4-hr	37%	30%
8-hr	54%	41%

While Table 5 shows how long the HVAC ran during unoccupied hours, Table 6 shows how much energy is associated with the on-demand settings. The increase in energy consumption is understandably greater due to the longer operating hours, but an increase in air handler fan speed to bring in more outside air is also a contributing factor.

Table 6. *Average daily energy (kWh/day) consumption comparisons of the different HVAC settings evaluated for 7 am to 7 pm on schooldays. Dates when HVAC was not functioning or when classroom was not fully utilized during COVID-19 were filtered out.*

"On-demand" HVAC setting	**N= Number of Sample Days**	**Average Daily Energy Consumption (kWh/day)**	**Average Power of HVAC when ON**	**Air handler fan speed setting**
1-hr	157	9.3	1.964	medium
4-hr	121	15.9	3.801	high
8-hr	78	18.9	4.003	high

4.5 Impact of on-demand settings and COVID-19 pandemic awareness on indoor CO_2

This study also evaluates the impact of on-demand settings on classroom CO_2 concentration. The 1-hr setting was in place up to the beginning of the pandemic in Hawaii. During that period indoor CO_2 levels periodically elevated beyond the ASHRAE recommendations [6] due to the intermittence of HVAC use, and that some users did not take advantage of the natural ventilation options [22]. There were also days during the warmer months when CO_2 readings likely exceeded 2,000 ppm but would not have recorded as such due to the sensor's upper limit. After instructor training was presented at the beginning of 2019, the CO_2 levels improved up to the end of 2019 when again values higher than 1,000 ppm were measured. CO_2 levels remained relatively low after the settings were modified to 8-

and 4-hours, largely because ventilation awareness was likely increased due to the recommendations made by the CDC and the State for fighting the COVID-19 pandemic. However, a trend of increasing CO_2 appeared during the last three months of the 2022 investigation period. The 2022 August and September data showed that CO_2 values increased, although well within an acceptable range, as clearly shown in Figure 29. This was due to a new fall-quarter cohort of instructors using the classrooms for the first time, who had not yet been trained in the optimal use of natural ventilation in the classroom.

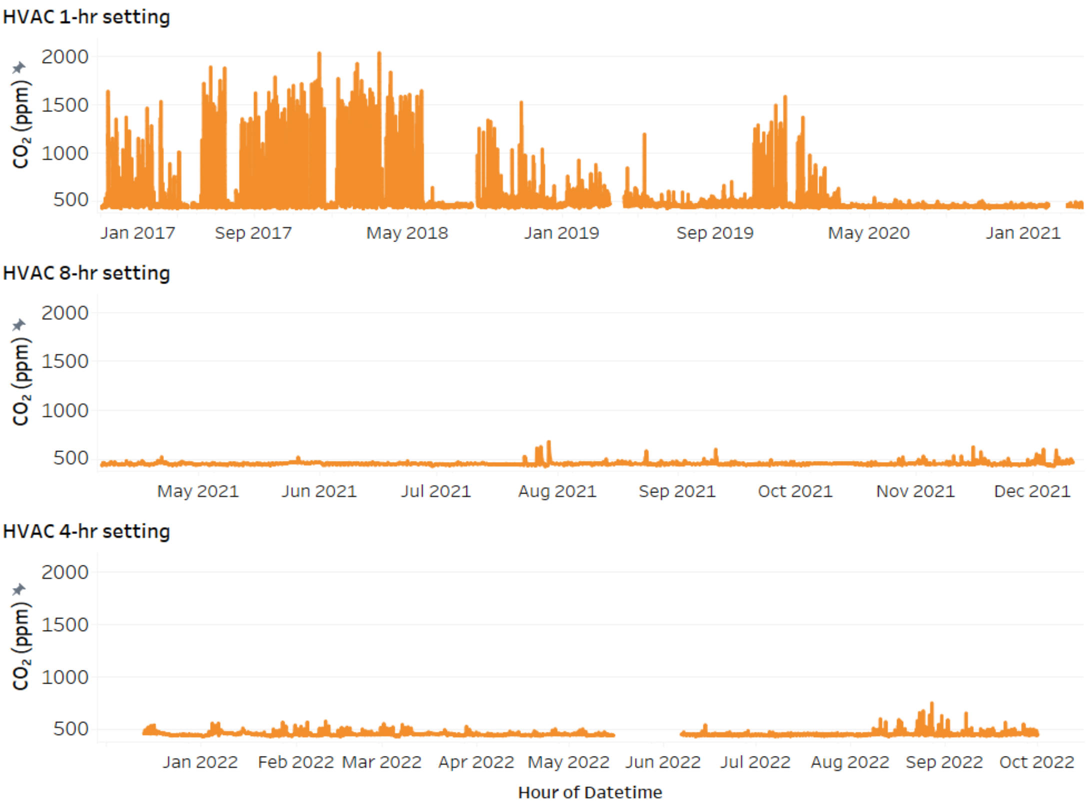


Figure 28. *CO_2 values by settings.*

4.5.1 HVAC, CO_2 and natural ventilation

There is a balance between HVAC energy use and CO_2 concentration that is a function of natural ventilation (window operation) and HVAC use for comfort. Figure 28-Figure 3 illustrate the relationships. Figure 28 shows that during early FROG 1 operation in 2017-18, Q1 through Q4, prior to instructor training, the HVAC was used regularly and CO_2 levels were among the highest observed during the entire study, with daily averages regularly exceeding 1,000 ppm. It appears from the data that natural ventilation features of the classrooms were not being used because traditionally windows are usually closed when HVAC is operating. After user training in 2018 which informed the instructors how to appropriately use natural ventilation rather than mechanical cooling, the CO_2 levels dropped significantly, Q1 2018-19. It should be noted here, that window sensors were installed in Q4 2018-19 in order to monitor window position. Prior to this, natural ventilation is only inferred by the observed levels of CO_2. Figure 29 illustrates that from Q1 2019-20 natural ventilation became more embraced, windows being opened more routinely. Additionally, prior to Q1 2021, the windows had been generally closed when the HVAC system was on, Figure 31.

After the return to classroom operation after a 17-month closure due to COVID-19, the windows were regularly opened concurrently with the HVAC on and CO_2 levels fell again to close to the background range. This is largely due to a heightened awareness of the need for fresh air and dilution. However, during the first quarter of the 2022 school year, Q1 2022-23, a new cohort of instructors was assigned to the FROG building and had not yet been trained in optimal use of the classrooms. As can be seen in Figure 30, HVAC use increased but the windows were not opened as frequently. CO_2 can be seen to increase slightly.

It can be seen from these heat maps that the operation of the classrooms is completely at the discretion of the user. In general, usage patterns among experienced users shifted from a conventional windows closed while air conditioning toward a concurrent HVAC operating mode, maximizing the amount of fresh air introduced through open windows. Untrained users' patterns were more mixed with the HVAC running regularly but less consistent about opening the windows.

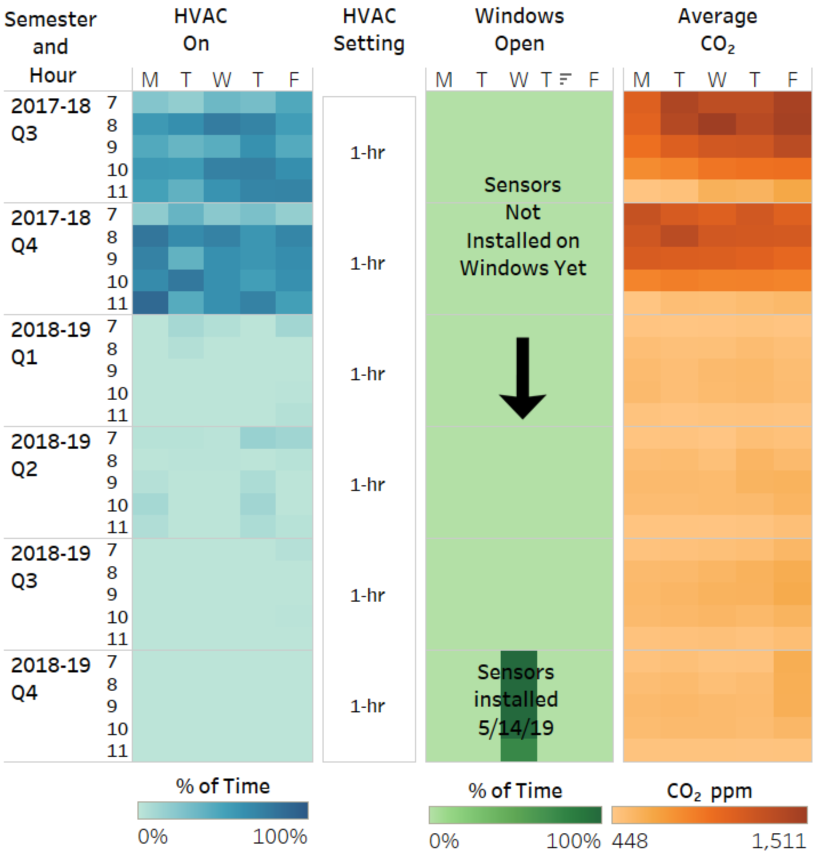


Figure 28. *HVAC use, CO_2 and windows open from Q1 2017-18 to Q4 2018-19. No data are available before Q4 2018-19 because the sensors reading if windows were open or not were not installed yet. HVAC on and Window Open are two independent variables, in the next chart the two are concurrent.*

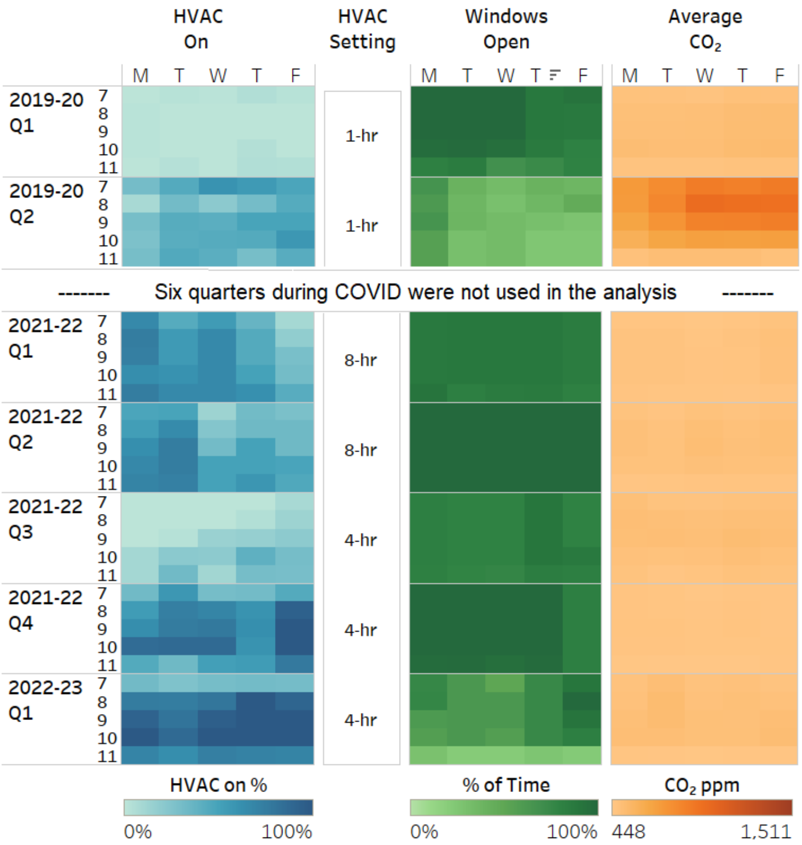


Figure 29. *HVAC use, CO_2 and windows open from Q1 2019-20 to Q1 2022-23. HVAC on and Window Open are two independent variables.*

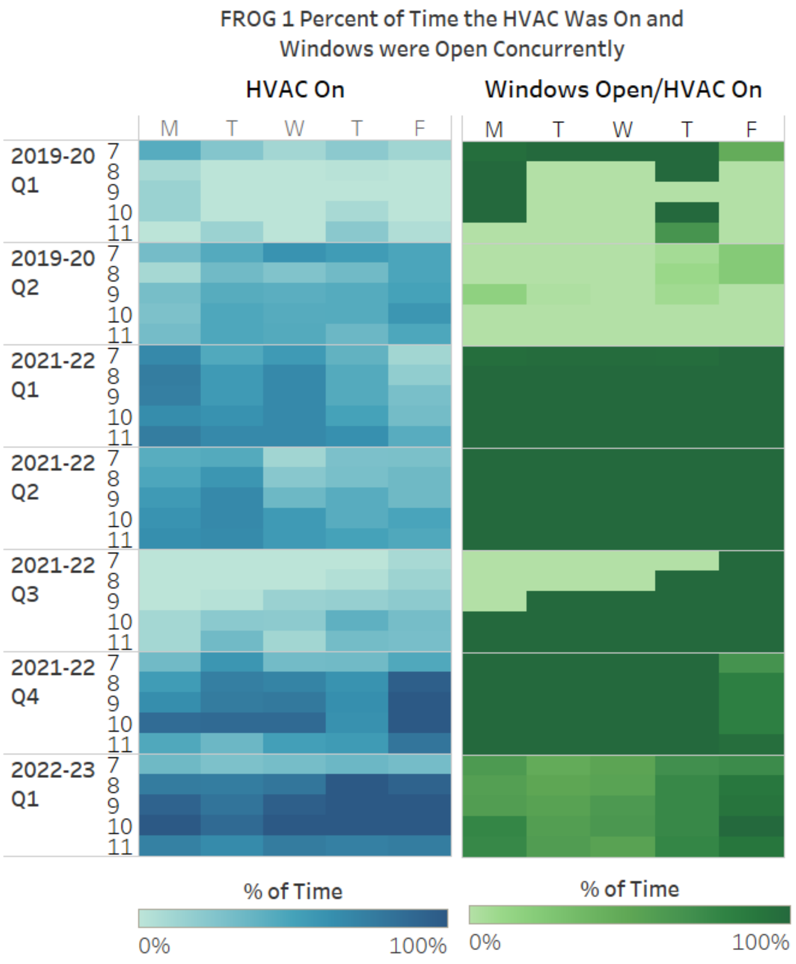


Figure 31. Percentage of time HVAC was on and windows were open concurrently. The "Windows Open" percentage is dependent on the HVAC condition but not the other way around.

4 Summary and Conclusions

As a response to environmental and indoor public health challenges, mixed-mode buildings provide an opportunity for users in tropical, cooling-only climates to control their indoor environment at a lower energy cost. On one hand, mixed-mode allows users to choose to open windows, doors and clerestories to increase ventilation rates. Conversely, mixed-mode can provide a false sense of well-being when the user feels that the choice between natural ventilation and air-conditioning is a binary decision and that either one will provide adequate ventilation. In many cases, because air-conditioning may not provide adequate fresh air, CO_2 concentrations are likely to increase without the user recognizing it.

With the 1-hr on-demand setting, the HVAC system was energized 28% of the time when the building was occupied. When set at 4 hours, the HVAC was on 37% of the time and 54% for the 8-hr setting. Energy savings is realized when the HVAC system does not waste energy by running when the building is unoccupied. With the 1-hour setting, the HVAC system was energized only 9% of time when unoccupied. With on-demand set to an 8-hr setting, the HVAC ran 41% of unoccupied hours. With the 4-hr setting, the HVAC ran 30% of unoccupied hours.

The 1-hr on-demand setting was in place up to the beginning of the pandemic in Hawaii. Because of the heightened awareness of the need for the circulation of fresh air indoors, HVAC runtime and fan speed was increased to facilitate the introduction of fresh outside air while the HVAC system was energized. After the return to classroom operation following a 17-month closure due to COVID-19, the increased awareness changed the behavior of experienced classroom users who had been using the room for several quarters. Not only did they take advantage of natural ventilation features such as operable windows, the also defied the conventional practice of *closing* windows while the HVAC was running. By running in *concurrent mode*, they opened windows while running the HVAC, and CO_2 levels remained low after returning to school following the pandemic closures. New users of the classroom were not familiar with the natural ventilation features of the classroom, and frequently ran the HVAC system without additional fresh air. While not rising to dangerous levels, CO_2 did rise with a new cohort of teachers in the fall of 2022.

A balance exists between HVAC energy use and indoor air quality (CO_2 concentration) that relies on natural ventilation (window operation) and HVAC use to maintain comfort as well as a healthy indoor environment. During early FROG operation in 2017-18, Q1 through Q4, prior to instructor training, the HVAC was used regularly and CO_2 levels were among the highest observed during the entire study, with daily averages regularly exceeding 1,000 ppm. Natural ventilation features of the classrooms were not initially being used because traditionally windows are closed when HVAC is operating. After user training in 2018 which informed the instructors how to appropriately use natural ventilation rather than mechanical cooling, the CO_2 levels dropped significantly. (Note: It should be noted here, that window sensors were installed Q4 2018-19 in order to monitor window position. Prior to this, natural ventilation was only inferred using the observed levels of CO_2. Data shows that from Q1 2019-20 natural ventilation became more embraced by the users, windows were opened more routinely. Prior to Q1 2021, the windows had been generally closed when the HVAC system was on.

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