Second Generation ZNE: Inheriting the Good Genes

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ABSTRACT

The energy performance of two second-generation, Project Frog zero net energy, component-built classrooms have on average improved on the first-generation ZNE Frog designs by up to 47%. Two new mixed-mode classrooms built on the University of Hawaii at Manoa campus, designed and constructed by Project Frog in collaboration with the UH Hawaii Natural Energy Institute demonstrate advanced lighting and HVAC control schemes as well as the impacts of user education and awareness. HNEI monitored energy consumed and generated at circuit-level, and recorded internal conditions to determine the relationship between comfort, environmental factors, energy demand and user response to new controls. A dashboard in each classroom delivers real-time visual feedback to users.

The actual energy performance exceeded both the predictive building simulation models as well as the first-generation all-electric ZNE structures also built by HNEI, realizing EUIs of 8.11 to 10.37 kBtu/sf/yr, excluding solar. This is in part attributed to improved lighting and daylighting controls, and especially a unique, on-demand approach to controlling the HVAC use. The On-Demand control reduced energy consumption 84% beyond a conventional thermostat scheduled for 7 a.m. to 7 p.m. operation. The On-Demand control is particularly effective in classroom environments where schedules and staffing vary daily and hourly over the week.

This case study of 5 buildings demonstrates that efficiency, advanced controls, user training and real-time feedback to users are key elements in the Frogs' successful performance.

Introduction

Between 2009 and 2012, three mixed-mode classrooms designed for zero net energy consumption by Project Frog were built in the state of Hawaii by the University of Hawaii's Hawaii Natural Energy Institute (HNEI) with funding from the Office of Naval Research. The buildings are used as elementary and middle school classrooms: one at Ilima Intermediate School on the island of Oahu, and two at Kawaikini School New Century Public School on the island of Kauai (see Figure 1). These buildings will be referred later in this paper as Ilima, Kawaikini East and Kawaikini West. Building performance was monitored by contractor MKThink of San Francisco and reported on in 2016 (Maskrey et al. 2016; MKThink 2016). In 2017, monitoring of these structures was recommissioned by MKThink after a year of hiatus.

A second generation of Project Frog zero net energy buildings, called UHM Frog 1 and Frog 2, were installed on the University of Hawaii and Manoa (UHM) campus in 2015-2016 to test design and fabrication modifications as well as new energy control systems. In addition to being used as classrooms for high school and university students, the structures are being used by HNEI as research platforms to: 1) test efficient building technologies such as energy storage, advanced occupancy sensing, advanced fan control and 2) gather data on actual interior conditions and perceived indoor comfort. The energy performance and environmental conditions are currently being monitored by HNEI with support from the UH School of Architecture's Environmental Research and Design Laboratory (ERDL).

This paper compares the performance of the two generations of zero net energy structures (Figure 1), the performance of innovative energy saving control strategies, and the influence of user preference and behavior on energy consumption.

Figure 1. First-generation Frog (left) with locations in Ewa Beach, Oahu and Lihue, Kauai. Second-generation Frog (right) located on the University of Hawaii at Manoa campus.

Background

Research Platform Design Features

Both generations of the all-electric Project Frog structures are component-based and assembled on site. The envelope design integrates basic energy efficient concepts: due north and south orientation to minimize solar gain; overhangs further shield the high performance, low-e glazing from solar gain; and the walls and roofs are well insulated.

The second generation Frogs benefit from more sophisticated lighting and HVAC controls. They utilize LED lighting with daylight harvesting controls that optimize lighting levels according to the amount of daylighting available within the space while the first generation uses T-8 fluorescents with daylight sensors. The second generation HVAC design is fine tuned for mixed-mode performance, delivering slightly higher temperature supply air in order to avoid condensation at the supply registers due to higher room humidity levels. On-Demand controls require users to make a conscious decision to turn the AC ON (i.e. a user preference), which allows the unit to run for one hour only. When the conditions require that it be restarted, the override button is once again pressed. In classroom situations where there may be long intervals between classes, and where users may have different room condition preferences, this feature results in significant savings if the button is not pressed again. As research platforms, the UHM Frog classrooms incorporate a real-time dashboard that displays current and past operating conditions, including indoor comfort indicators, as well as the energy used by different end-uses. Intended as an educational tool, the dashboard and supplemental training for instructors aimed to foster more conscious energy efficient behavior by allowing the building occupants to visualize their energy usage and PV generation.

A comparison of the energy features of both generations of Frogs are listed in Table 1. They share common features such as envelope insulation and glazing, however the lighting, HVAC and approach to natural ventilation are different.

Table 1. Energy features of two generations of Frog buildings

Energy Features 1st Generation Frog (1,280 sf)	Energy Features 2nd Generation Frog (1,440 sf)
• R-24 walls; R-30 roof decks. • Operable louvers at the base of the solid wall panels for natural ventilation. • High and low operable windows for natural ventilation. • Low-e, PPG Solarban 70XL glazing (SHGC=0.27; U=0.24; VLT=64%). • Roof mounted exhaust fan at high point of the roof for fan induced ventilation. • Direct/Indirect fluorescent T8 lighting with photosensor daylight control. • Nine speed, variable speed ceiling fans. • High efficiency split system fan coil and condensing unit (EER 11.0). • North-South orientation • PV systems: 5.24 kW per structure. • All electric, no natural gas on site	• R-24 walls; R-30 roof decks. • High and low operable windows for natural ventilation. • Low-e, PPG Solarban 70XL glazing (SHGC=0.27; U=0.24; VLT=64%). • External shade structure on south glazing. • Direct/Indirect LED lighting with daylight control. • Six speed, variable speed ceiling fans. • High efficiency split system fan coil and condensing unit (EER: 11.8). • North-South orientation. • PV systems: 8.0 kW per structure. • All electric, no natural gas on site

Building Performance Monitoring

The first generation Frogs were instrumented and monitored for three years, ending in 2016 and recommissioned mid-2017. The second generation Frogs were instrumented and monitored from September 2016. Table 2 summarizes the sensing points for both generations.

Table 2. The sensing points for the environmental and energy data

Electrical circuits	Indoor	Weather
• HVAC condenser • HVAC fan coil • Lighting (internal and external) • Ceiling fans • Solar PV • Exhaust fan (1st Gen. only) • Panel feed	• Room air temperature • Wall surface temperature • Supply and return air temp. • Relative humidity (room, supply and return duct) • CO2 concentration • Illumination • Air speed (1st Gen. only)	• Ambient temperature • Relative humidity • Solar radiation • Wind speed • Wind direction

Comparative Results and Findings Across Five Frogs

When comparing Energy Use Intensity (EUI) between the first and second generation Frogs, on average the second generation uses approximately 47% less energy per square foot than the first generation (Table 3). Consumption data for the second generation is from the calendar year 2017, but calculated rather than actual PV data was used since it was installed in late 2017. Consumption data for the first generation are from August 1, 2017 through January 31, 2018 (six months) and doubled for a one-year estimate. Since the PV generation was lower for these months and not representative of a full year, the 2014-2015 school year PV data was used.

Table 3. Source energy use intensity (EUI) for 2017

	1st Generation Frog			2nd Generation Frog	
	Kawaikini East	Kawaikini West	Ilima	UHM Frog1	UHM Frog2
Total annual electricity energy (kWh/yr)	5,549	2,165	11,942	4,376	3,421
Actual EUI (kBtu/sf/yr)	14.79	5.77	31.83	10.37	8.11

Energy disaggregation of all five Frogs can be seen in Figure 2. On average, less energy is used for both lighting and HVAC systems in the second generation than the first generation. Ceiling fans make up a larger proportion of the energy consumed in the second generation by virtue of the smaller lighting and cooling loads. Led by conscientious instructors, Kawaikini West has developed over time into an anomaly where users have embraced energy efficient practices, using very little air conditioning and taking full advantage of natural daylighting.

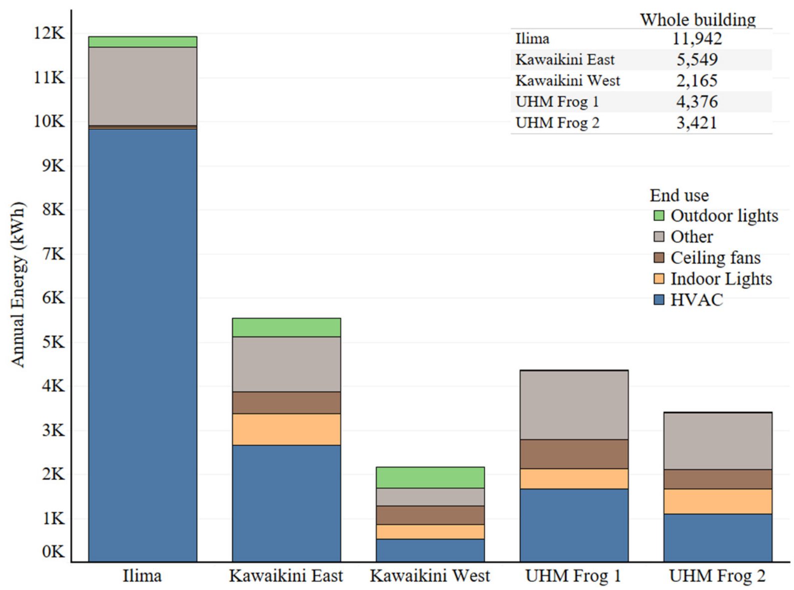


Figure 2. Energy disaggregation all five Frogs in 2017.

Addressed in the User Education and Behavior section to follow, when the occupants are committed to reducing energy and are flexible in their adaptation to comfort within their environment (Deuble et al. 2012), EUIs may be minimized as exemplified by the EUI of 5.77 kBtu/sf/yr for Kawaikini West.

Overall energy generation and consumption across the five Frogs is illustrated in Figure 3. Conspicuously, the Ilima Frog has not hit its zero net energy targets over the past year, with consumption exceeding generation by 29%. This is due to a higher than anticipated use of air conditioning in the classroom, which is located in one of the hottest regions of the state.

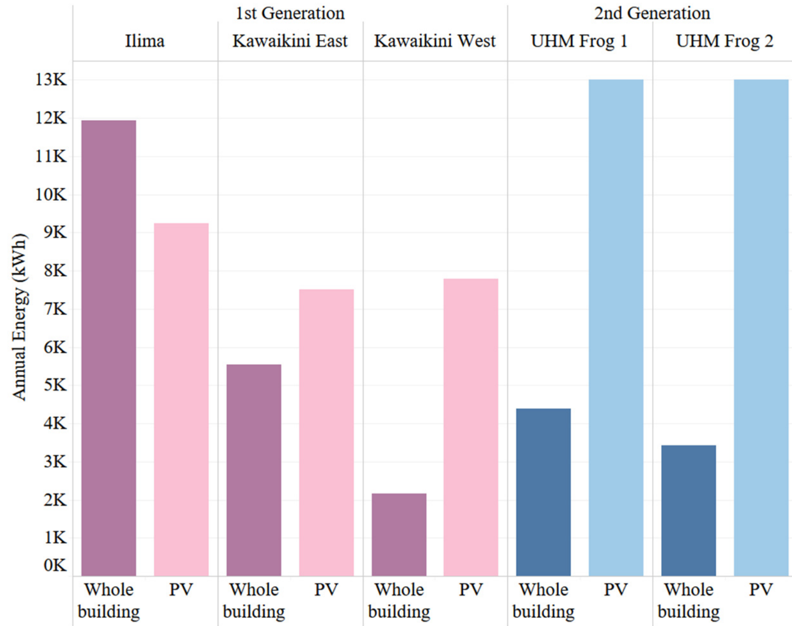


Figure 3. Overall energy generation and consumption comparison of five Frogs in 2017.

All of the other Frogs are hitting their zero net energy goals. The photovoltaic systems for the UHM Frogs are significantly oversized relative to their current consumption. The operating hours assumed in the design phase are greater than the current operating schedule, but as the buildings' utilization increases, the loads are expected to grow.

Second Generation: UH Manoa Frogs

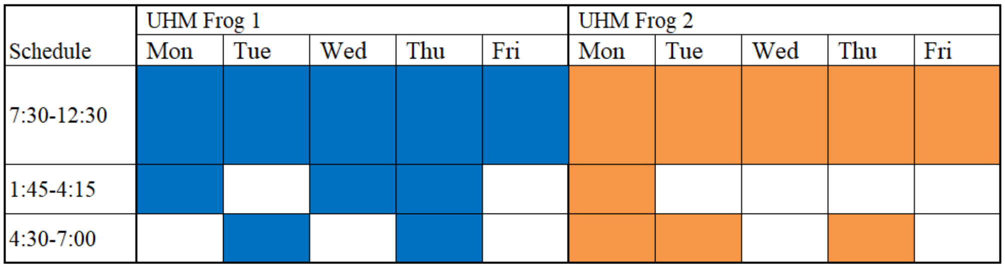
General Information

The UHM Frogs are multi-purpose classrooms whose schedules vary daily throughout the week. The mornings are used consistently by a UH-based charter K-12 school, while the afternoons are used by the UH College of Education, with one or two classes conducted through the afternoon and evenings. Classes may be held from 5 to 10 hours per day over a 12-hour period. The schedules are dynamic in that they change every semester, and to date they are currently operating at an average of 71% of capacity, non-inclusive of extracurricular weekend activity.

These mixed mode buildings are designed to actively engage users while utilizing some degree of automated controls. The lighting utilizes daylight harvesting sensors to reduce lighting energy, although users are encouraged to manually turn the lights completely off when the daylight is adequate to meet class-specific needs. HVAC utilizes an On-Demand control that requires user engagement to activate, but automatically shuts off after one hour. Ceiling fan operation is 100% manual, utilizing a variable speed wall switch. The impact of this hybrid approach to engage the user is discussed later in the Results portion of the paper.

Data analyzed for this paper are from the fall 2017 semester (August 20-December 16, 2017; 119 days), after instrumentation commissioning was complete and regular classroom scheduling was implemented (previous semester trial schedules were irregular). The period includes 81 school days and 38 non-school days (weekends + holidays). The building schedules differ slightly as shown in Table 4, with Frog1 having approximately 10% greater classroom occupancy hours than Frog 2.

Table 4. UHM Frog 2017 fall semester schedule



Energy consumption is distributed among five primary end-uses: HVAC, lighting, ceiling fans and other that includes telecommunications, fire alarm, multi-media, and misc. plug loads, see Table 5 below:

Table 5. Energy summary by disaggregated loads (August 20 – December 16, 2017)

	Air conditioning (kWh)	Ceiling fans (kWh)	Indoor lights (kWh)	Other loads* (kWh)	Whole building (kWh)
	Fall 2017 Semester (24h/7days)				
UHM Frog 1	866	283	212	577	1,938
UHM Frog 2	576	229	222	500	1,528
	Fall 2017 Semester for Scheduled Occupied Hours				
UHM Frog 1	632	147	132	219	1,130
UHM Frog 2	409	149	103	197	858

*Other loads=Plug loads + Telecommunications + Multi-Media + Fire alarm

Due to the user engagement required to optimize the utilization of the UHM Frogs, education and training are essential. Currently, brief training sessions are held for the instructors using the rooms. In addition, an engaging poster with cues on basic building operation are placed in each classroom. Finally, a dashboard is mounted in each room providing real-time feedback on daily and year-to-date energy generation, daily energy consumption by end-use, and comparative results to the other Frog.

Results

Daylight Harvesting and Lighting Controls

Lighting energy in the UHM Frogs is controlled by two types of wireless sensors and a control module. Two wireless Lutron Pico occupancy sensors per classroom activate the lights when entering the room. A Lutron QSM daylight sensor mounted on the ceiling automatically sets the light levels according to ambient conditions. A Lutron Energy Saver Node Module interfaces with the daylight and occupancy sensors to manage the lighting operation according to user-programmed criteria. In the main room, four rows of Lutron Lantana LED fixtures are controlled by one occupancy sensor and one daylight sensor. In the entry zone, 2 rows of fixtures have identical controls. The rows are pre-programmed to operate at light levels determined by their distance from the windows. On a typical sunny day, approximately 30 seconds after the lights are activated by the occupancy sensor, the fixtures will dim to the minimum Illuminating Engineers Society (IES) standards required for the space, with the perimeter row dimming to about 10%, the center row to about 25% and the interior row to about 40%. The fourth bank located in the rear of the room, is also at about 40%. On overcast days and evenings, the fixtures will ramp up output accordingly.

The impact of this control configuration is illustrated in Figure 4a. Various sensor configurations are compared for a hypothetical day with a full schedule. No controls would use the lights at full brightness (0.47 kW) from 7 a.m. to 7 p.m. The occupancy sensor (OS) would turn off lights during the breaks between sessions, saving 13%. The daylight harvesting (DH) in addition to OS is estimated to save 35%.

Considering a full semester, if there were no controls and lights used at full brightness from 7 a.m. to 7 p.m., 457 kWh would have been used (Figure 4b). However, the schedule was only filled 74% and 68% of capacity (see Table 4 but percentages account for hours users did not occupy the buildings at their scheduled time), resulting in a reduction to 340 kWh and 309 kWh from the OS (26% and 32% savings). The users manually turned the lights off 43% to 48% of the time they occupied the buildings, reducing the energy to 192 kWh and 160 kWh, leaving less need for daylight harvesting which reduced the energy to 139 kWh and 113 kWh.

As will be discussed in the User Education and Behavior section, the most effective intervention is manual, where the user turns the fixtures off completely, using only daylighting to deliver slightly less than IES standards. In these Frogs, natural daylight can provide adequate light most of the daytime hours.

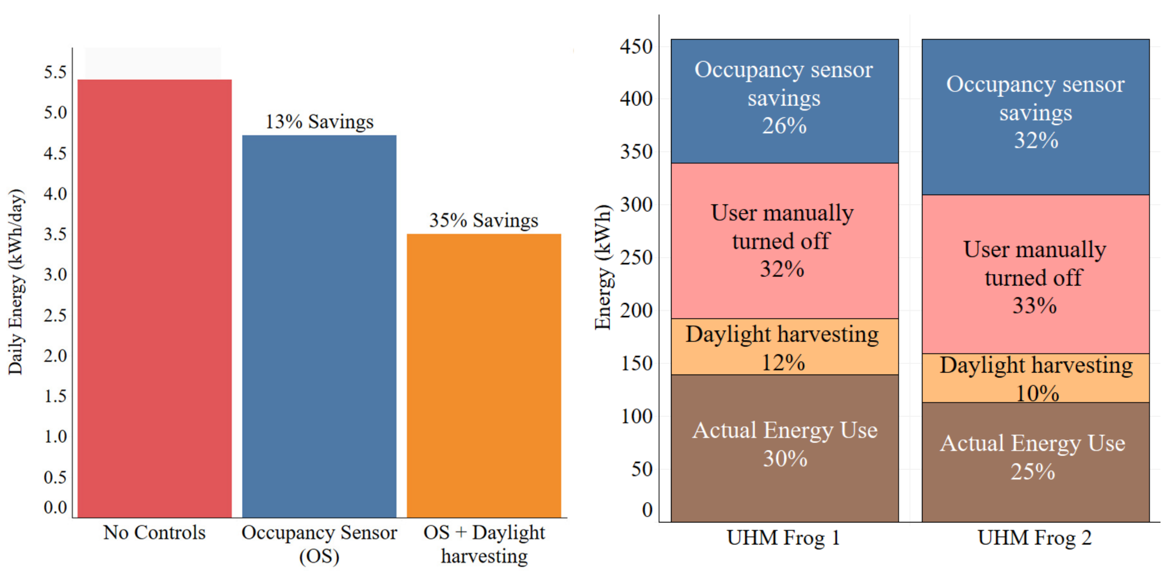


Figure 4 (a) Average daily energy consumption and percentage savings of lighting control intervention options for a hypothetical day with a full schedule; (b) Actual energy used and percent savings for the full semester for school days.

HVAC Controls

Classrooms in a university setting have dynamic schedules that may vary significantly by day over the course of a week. The UHM Frogs were outfitted with an On-Demand control for the HVAC system to reduce run time when there are no occupants in the building. In addition, the On-Demand control requires user engagement and decision-making (called technological or environmental adjustment in Azizi et al. 2015), increasing the awareness of building operation.

The On-Demand system integrates the functionality of a vacancy sensor and a timer. In order to run the HVAC, the user must consciously decide that cooling is required, then engage an override switch that turns the system on for an hour. After the system turns OFF, the user must decide whether the interior conditions warrant a second hour of cooling.

To illustrate, Figure 5 presents two energy profiles for one day, one with a conventional thermostat, and one with an On-Demand thermostat. Based on five-minute averages of the occupied periods over the entire semester, the On-Demand control shows an 84% reduction in energy consumption over the daily energy that would have been used absent controls to limit its operating time.

Another design modification was incorporated into the UHM Frogs, specifically to address issues that can face mixed-mode buildings. Mixed-mode buildings utilize both natural ventilation systems and mechanical systems, frequently on the same day. In humid regions, bringing in air through operable windows also introduces moisture to the space. In the Frog design, the design supply air temperature was elevated to 65ºF rather than conventional 55ºF supply air temperature, in order to avoid condensation at the supply air registers that could result from the elevated humidity.

The setpoint for the On-Demand controller is 77ºF. While the indoor air temperature does not always reach the setpoint, the variable speed ceiling fans provide air motion whose comfort perception is equivalent to approximately 3-6 ºF reduction of air temperature.

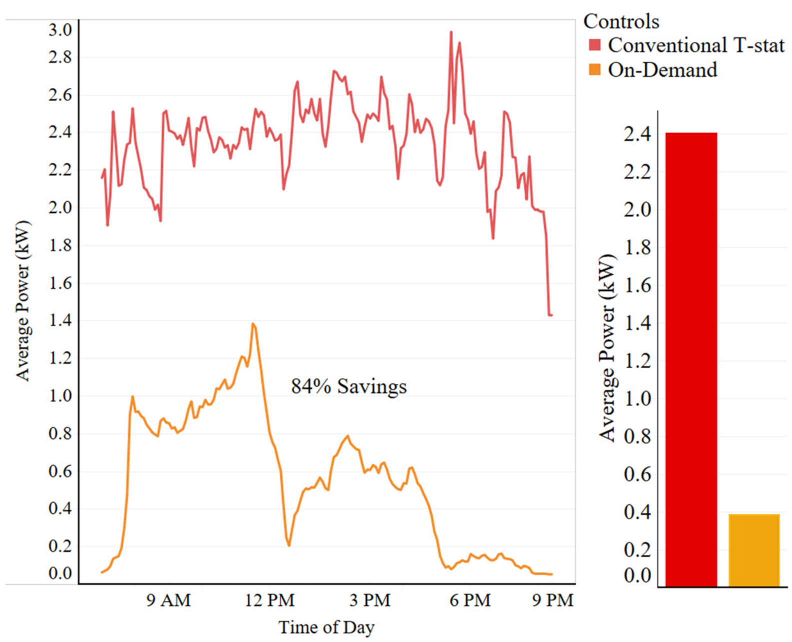


Figure 5. Comparison of Conventional vs On-Demand HVAC control (5 minute average data).

User Education and Behavior

User behavior and response to a building's condition can impact energy end-use even more than automated controls.

Indoor lighting

The UHM Frogs were designed to rely heavily on natural daylighting and daylighting controls. When comparing occupancy sensing controls, daylight harvesting sensors and the human factor of choice (to turn off the lights), the user initiated response saved the greatest amount of energy (Figure 4b). If the schedule utilization increased from the current 74% and 68% to 100%, the user choice will represent the largest energy savings by far.

Figure 6 indicates that different user preferences will impact the decision to switch the lights ON or OFF. A noticeable difference in lighting energy use is seen between the two Frogs, indicating that one classroom is more energy conscious; or the classes require more lighting to reach their educational mission (e.g. art may require greater visual acuity); or a pattern due to habituation to turning lights on has developed over time. The illustration shows that user-choice significantly impacts energy use in otherwise identical classrooms.

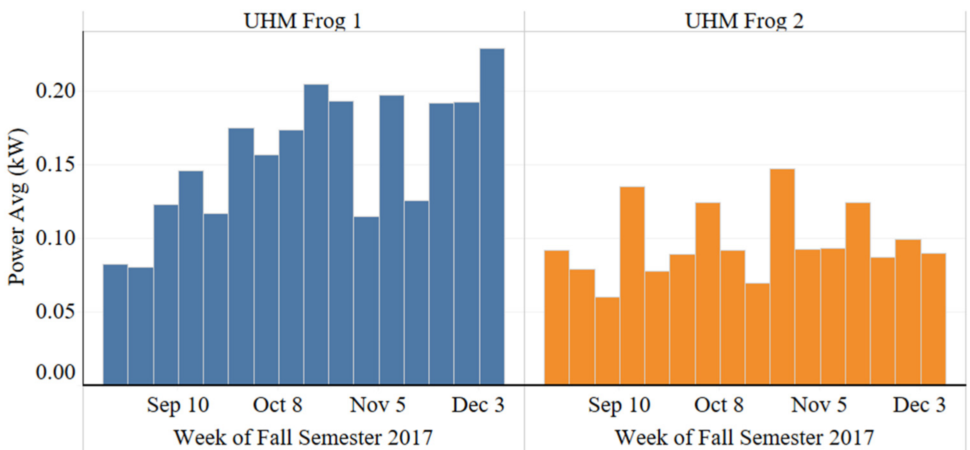


Figure 6. Weekly average lighting power for afternoon class session for occupied hours.

Air conditioning

A mixed mode building is also dependent on user response to the interior conditions. While the intention is to minimize use of mechanical cooling and rely primarily on natural ventilation through open windows as well as ceiling fans, user preference and/or operational awareness (again technological or environmental adjustment, Azizi et al. 2015) can impact their response. One type of user prefers the fresh air and wishes to save energy. Another user may activate the air conditioning without regard to energy; while yet another is indeed responsive when properly informed of the intent and features of a special zero net energy building, and is willing to physically open and close the windows as necessary.

User behavior in these two buildings can be observed in several dimensions. As suggested in Figure 7, after a training session was offered during the first week of classes, HVAC consumption dropped whereas consumption in Frog 1 increased. The pattern reflects conscientiousness over HVAC energy system use in the Frog 2 classroom that is not reflected in Frog 1. While this was not a target of rigorous evaluation in this study, anecdotal input from the instructors indicates that training and awareness of how the systems operate affect behavior and overall consumption. The impact of reduced HVAC operation is of course, higher temperature. But as it has been observed by previous researchers (Deuble et al. 2012), occupants with a higher level of environmental concern were more forgiving of their building and prepared to overlook less-than-ideal conditions as compared to less environmentally-conscious occupants. The temperature differential for the two mixed-mode buildings over the entire semester averaged 1.34ºF: Frog 1 averaged 79.47ºF and Frog 2 averaged 80.81ºF.

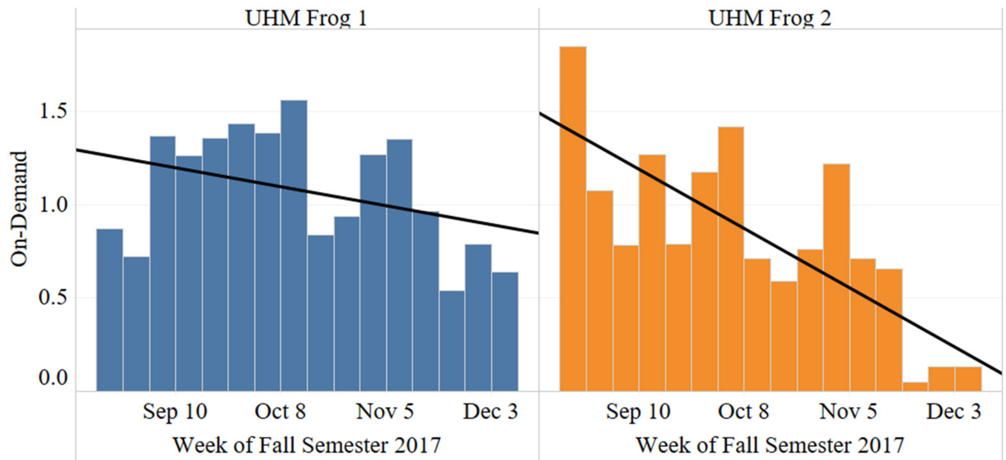


Figure 7. Weekly average of HVAC power for morning class session for occupied hours.

The second dimension to decision-making and behavior relates to decision mid-session. Once a decision has been made to turn on the On-Demand HVAC, a secondary decision will be when the one-hour ON time period is over. The user must answer the question, "Are we comfortable enough to not need a second hour?" With ceiling fans running, the interior conditions must be assessed against the current comfort levels. If conditions are currently acceptable, a conscious decision can be made to not run the HVAC for a second hour.

A third level of decision-making relies on the awareness of how the building operates, and a commitment to the proper operation of a zero net energy building, primarily dependent upon education and training. We have observed that even though there were only 10-15 minutes left of class, the one-hour override switch was pushed, leaving at least 45 minutes of cooling an unoccupied space. With a conscientious approach, a user might elect to forego HVAC for few remaining minutes of a class with the knowledge that much of it will be wasted. Alternatively, they can turn the system ON, but as aware users, manually turn it OFF when leaving the classroom. These situations require insight into how the controls operate as well as philosophical "buy-in" into the design intent of the facility. This insight is gained though comprehensive and effective training of the users.

Air quality

Another factor to consider when operating a mixed-mode building is that of air quality, specifically CO2 concentration. In the UHM Frogs, a CO2 build-up was noticed when the HVAC was running, and presumably the windows were not open (Figure 8). The CO2 concentration increased even more after the HVAC turns off, presumably because they still occupy the building but have not opened the windows. Conversely, when running in a naturally ventilation state, the windows were open and CO2 levels remained low. Over the course of the semester and during occupied hours, the Frog 1 consistently ran the HVAC system more than the Frog 2 (Table 5). Figure 9 shows consistently higher CO2 concentrations in Frog 1 in the morning session while the building used HVAC more (Figure 7). Figure 10 shows an increase in CO2 concentration in Frog 1 over the semester, suggesting that the habit of not opening the windows continued even though the need for HVAC was less as the outdoor temperatures decreased over the fall. The reduction in HVAC use can be seen by trend line in Figure 7.

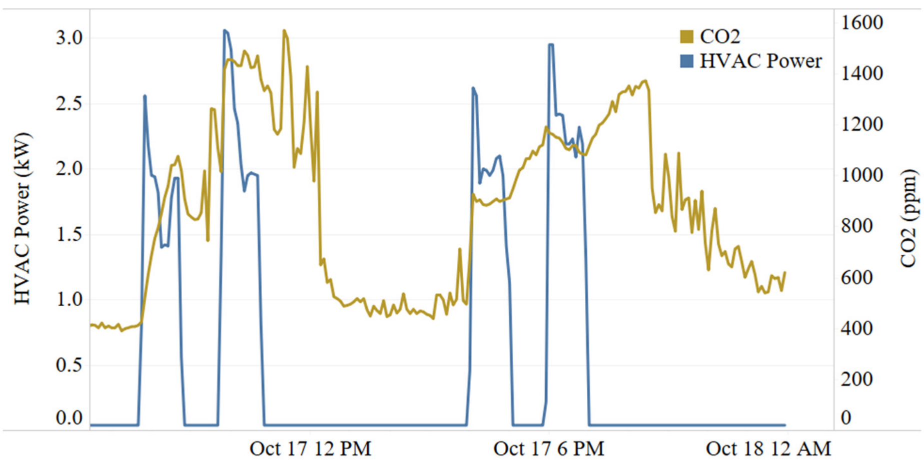


Figure 8. Example of CO2 concentration increasing as users remained in building after HVAC turned off (assuming the windows were still closed).

	UHM Frog 1					UHM Frog 2				
Hour..	Mon	Tues	Wed	Thur	Fri	Mon	Tues	Wed	Thur	Fri
7	454	506	549	468	476	442	446	445	447	457
8	749	776	752	706	721	587	555	525	575	602
9	959	934	862	913	895	680	628	543	678	706
10	1,102	1,086	1,056	1,082	1,020	737	664	566	722	721
11	1,151	1,072	937	1,106	1,120	738	692	558	784	709
12	920	840	716	949	984	671	635	500	720	704

Figure 9. Average CO2 concentrations (ppm) for the morning session for the fall 2017 semester.

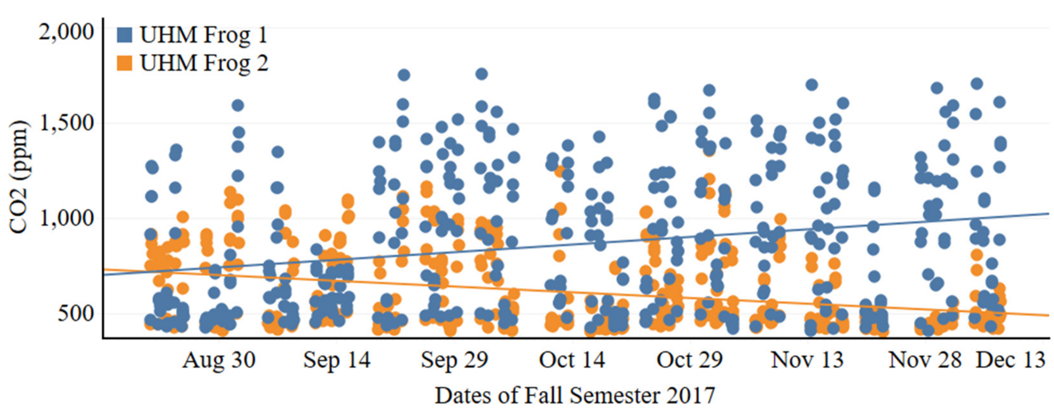


Figure 10. Hourly average CO2 concentrations for the morning session during occupied hours.

Conclusions and Recommendations

Based on the initial observations of the UHM Frogs, the second generation design has the potential to outperform the first generation design. However, user response to interior conditions and use of the operable features of the buildings, HVAC, lighting, ceiling fans, and windows, will be the primary driver in determining overall energy consumption.

While one of the first generation Frogs achieved an EUI of 12.9 kBtu/sf/yr in the 2015 study year, recent 6 month observations reduce it to an equivalent of 5.77 kBtu/sf/yr.

The second generation lighting system controls, i.e., occupancy sensor and daylight harvesting, contribute at least 35% savings, but considering user behavior of choosing to turn lights off total savings of up to 75% resulted.

Limiting the duration of HVAC operation by using an On-Demand thermostat, savings of up to 84% were observed. These reductions are due to the HVAC system operating only when users are present as well user opportunity to consider natural ventilation options. The On-Demand thermostat is a mechanical equivalent to a vacancy sensor as it must be manually activated, and will automatically shut off.

Future interventions that will improve overall performance include:

- Provide comprehensive education and training to all users, not simply the instructors, but classroom users (students) as well. This can be done with online mini-training; in-person; or through a “train the trainers (instructors)” approach.
- Reprogram the lighting controls to vacancy sensing, requiring the lights to be manually turned ON between the hours of 8 p.m. and 5 p.m., rather than automatically turned on with an occupancy sensor. Natural daylight may be adequate for classroom purposes.
- Install actuators on manually operated windows will overcome one barrier to natural ventilation: the time-consuming task of opening a multi-window banks of windows.
- Install occupancy sensors for fans.

Acknowledgements

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