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Microwave Doppler Radar Occupancy Sensing for HVAC Energy Savings

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ABSTRACT Buildings consume about 30% of the world's energy, and produce 37% of global energy-related CO_2 emissions. Building energy efficiency is becoming even more critical as climate change related events take a toll on human life, and further increase building energy consumption due to higher cooling needs. Reducing building energy consumption is imperative to break this detrimental cycle of harmful emissions creating more energy demand. Occupancy sensors play a crucial role in building energy efficiency by optimizing the operation of lighting, heating, ventilation, air conditioning (HVAC) and other systems based on the presence or absence of people. Microwave radar-based occupancy sensors offer improved accuracy, versatility, and coverage range over other occupancy sensors, while remaining non-intrusive and low-cost. However, building energy savings from usage of radar-based occupancy sensors has not been widely documented. Here, we show that microwave occupancy sensors, installed in an academic office building in Hawai'i can be used to manage HVAC schedules, ultimately providing energy savings of over 6 kWh/yr/sf, about 20% reduction in energy usage for this building. These results demonstrate how controlling energy consumption based on microwave occupancy sensing can greatly reduce building energy consumption which is crucial for controlling climate change.

INDEX TERMS Occupancy sensing, HVAC, Doppler radar, building energy, microwaves in climate change.

I. INTRODUCTION

Climate change related events take a significant toll on human life, estimated to result in 83 million excess deaths between 2020 and 2100 [1], making climate change the most important global challenge of this century [2]. Buildings account for about one third of global energy consumption and related emissions contributing to climate change [3], and their impact is rising with increasing cooling needs, especially in urban areas in the developing world [4]. While climate change is reducing heating demand in some geographic areas, increased cooling demand in warmer climates is much more significant due to higher population density [5]. Both high energy demand of air-conditioning (AC) systems, typically met by burning fossil fuels, and refrigerant related greenhouse gas (GHG) emissions, contribute to climate change [4]. Thus, reducing building AC use is imperative to break this detrimental cycle of harmful emissions creating more energy demand.

Improving energy efficiency, together with fossil fuel reduction and carbon capture, is a critical strategy for addressing climate change [6]. In the building operations sector, occupancy based controls are a promising approach for improving energy efficiency. Occupancy data can be a valuable tool in optimizing energy consumption in buildings through smart lighting control, heating, ventilation, and air conditioning (HVAC) systems optimization, energy-efficient equipment activation, plug load control, predictive maintenance, space utilization optimization, demand response programs, data-driven decision-making, and integration with building automation systems. By leveraging occupancy data in these ways, building owners and operators can significantly reduce energy consumption, lower utility costs, and contribute to environmental sustainability.

Inaccurate assumptions of building occupancy can result in wasted energy on plug loads, lighting, and HVAC. HVAC systems can consume a significant amount of energy, accounting from 40% to over 70% of a building's total energy consumption, depending on building use and geographic location [7]. The potential energy-savings of occupancy-based control of HVAC has been studied [8], but this technology is not widely adopted. Even though occupancy sensing lighting controls are relatively common, approximately only 17% of commercial buildings in the United States had a functional occupancy sensing system installed as of 2018 [9]. HVAC control is mostly implemented through temperature set points and scheduling, providing modest energy savings.

Passive infrared (PIR) and ultrasonic (US) occupancy sensors are most commonly used for lighting controls, however they both have limited accuracy and are subject to placement restrictions [10]. To overcome these limitations, other technologies including hybrid PIR and US, video, CO_2, and radar have been investigated [10], [11], [12]. Radar occupancy sensors have emerged as dominant technology for in-cabin automotive applications, due to their reliability and privacy preserving features [13], [14]. This technology has also been demonstrated effective for building occupancy sensing [15], [16], [17], [18], including occupant count [19]. A Doppler radar sensor can provide a wide coverage area while maintaining high enough sensitivity to resolve motion as small as that caused by a heartbeat. Furthermore, Doppler radar is not subject to interference from light, heat, ventilation, or sound.

This paper describes microwave radar-based occupancy sensing system implemented to save building energy by informing HVAC scheduling. The sensing system consists of multiple sensors and data user interface used to track and display office space use over a designated time period (Fig. 1). Six Doppler radar-based occupancy sensors were installed in three separate office spaces in an office building on the University of Hawai'i at Mānoa campus [20]. The data was recorded over an eight-month period and analyzed to make recommendations for modifications to the HVAC schedule. This paper describes sensor system design and implementation, occupancy data analysis, and calculations of energy savings achieved based on occupancy data. This is the first long term occupancy study using microwave sensors, demonstrating significant energy savings benefit of over 20%, with a potential to help break the detrimental cycle of harmful emissions contributing to climate change.

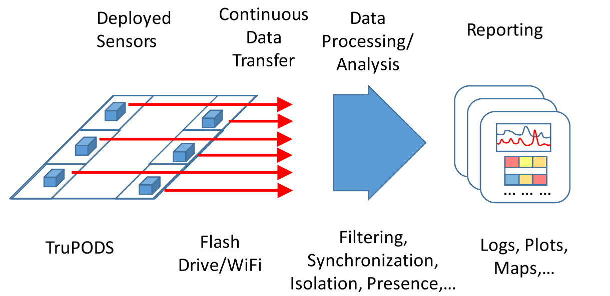


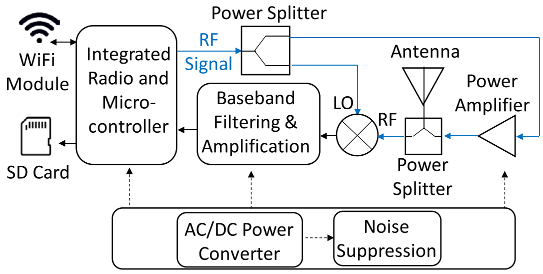
FIGURE 1. Overview diagram of microwave occupancy system used in the occupancy study.

FIGURE 2. Photograph of one of the deployed microwave occupancy sensors.

II. MICROWAVE OCCUPANCY SENSING SYSTEM

The occupancy sensing system used in this work consisted of six microwave sensors with integrated digital recording and wireless communications that plugged directly into wall power outlets, signal processing software for detecting presence events, and a graphical data user interface for identifying trends in the data. Fig. 2 shows a photograph of one of the deployed sensors. The entire sensor was adapted to be completely contained in a standard outdoor single-outlet receptacle cover in order to conform to the requirements that the device be unobtrusive, minimally affect existing infrastructure, and use a standard UL-listed connection to an existing AC power outlet. While the sensors support Wi-Fi-based wireless communications for data transfer, this particular deployment imposed restrictions which resulted in the data being collected manually on a weekly or monthly basis using the built in Secure Digital (SD) card flash-drive recording capability. The system included a custom Web-based user data platform which provided various means to analyze the results including logs, plots, heat-maps, etc., which could comparatively display occupancy data over specified time periods. The design and optimization of the displays were also part of the occupancy study project.

The radar-based occupancy sensors used in this work were developed based on the Adnoviv TruePODS sensor [18], [21]. The sensor uses radar technology to recognize human physiological motion in the vicinity, and is intended to effectively sense both moving and sedentary occupants. Sedentary occupants are often not detected by the commonly used PIR



Carrier Frequency	Power to antenna	Beamwidth
2.4-2.5 GHz	16 dBm	60° x 80°

FIGURE 3. Block diagram and specifications for the microwave occupancy sensor.

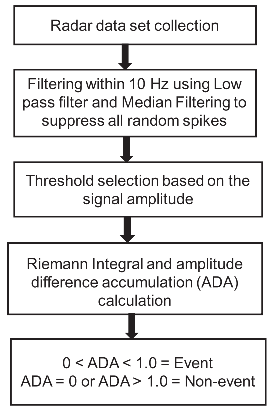


FIGURE 4. Flow chart for algorithm used for occupant presence determination.

and US occupancy sensors, such that occupants need to wave at the sensors to get the lights to turn back on [10]. This often leads to complete disuse of these sensors which makes such technologies particularly problematic. Furthermore, radar based sensors can be used for greater range and coverage, with a single TruePODS sensor designed to cover rooms up to 100 m^2 and demonstrated for vital signs sensing throughout a 3.4 m × 8.5 m conference room [18]. Radar based sensors are also better suited to detecting the submicron displacements associated with cardiopulmonary activity, particularly at millimeter wavelengths [22].

A. HARDWARE

Fig. 3 shows the block diagram of microwave occupancy sensor. The sensor is implemented with an integrated 2.4-GHz radio and microcontroller, which generates the RF signal necessary for radar transmission and demodulation of the return signal. A portion of the generated RF signal is amplified and sent to the air-gap antenna that is integrated within the sensor enclosure. This continuous wave (unmodulated) signal is transmitted into the coverage area. The custom air-gap patch antenna has a full-width half-maximum of approximately 60° × 80°. The signal reflects off objects in the coverage area, and the return signal is thus modulated by any motion in the area, including occupant ambulatory motion and the respiratory motion of sedentary occupants. The reflected signal is received by the same antenna, and directed to a radio mixer, which demodulates the signal. Following baseband filtering and amplification the signal amplitude is roughly proportional to the motion in the space. This signal is digitized by the integrated radio and microcontroller. Processing to determine occupancy vs. vacancy can be performed by the microcontroller, but in this case, the raw data was recorded to enable testing of multiple processing approaches. The resulting data is then logged to an SD card or transmitted via the integrated Wi-Fi Module. The processed data is then uploaded to a custom data service platform for further analysis.

B. SIGNAL PROCESSING

The algorithm used to determine occupancy vs. vacancy from the microwave occupancy sensor data makes use of the Riemann integral of the radar output. The flow chart for the algorithm is shown in Fig. 4.

The baseband output signal from radar sensor can be expressed as:

$$x_r(t) = A\cos\left(\frac{2\pi}{\lambda}\left(2d_0 + 2d(t)\right)\right), \tag{1}$$

where λ is the wavelength of the transmitted signal, d_0 is the static distance of radar antenna to the human subject, *d(t)* represents cardiopulmonary or other displacement, and *A* is the amplitude of the received signal. The displacement relates to the phase in the equation above in the form of:

$$S(t) = \frac{4\pi}{\lambda}dt. \tag{2}$$

An energy spectrum method is used to recognize body movements. Using a sampling rate of 100 Hz for the demodulated signal, *S(t)* is diveded into continuous non-overlapping windows S_k of 60 seconds. In the *k*-th window, the Riemann integral $A_k(i)$ of S_k, with respect to the 10-second period is defined as:

$$A_k(i) = \sum_{t=t_k-i*1000}^{t_k-(i-1)*1000} |S_k|\,dt, \tag{3}$$

where t_k denotes the time of S_k. $A_k(i)$, *with* $i = 1{:}6$, is calculated every ten seconds. The algorithm reports body movement and activity if there is a change of more than a preset threshold of $A_k(i)$.

Since body movements vary in both amplitude and frequency, amplitude difference accumulation (ADA) of the motion is used to confirm the Riemann integral, and threshold crossing to decide between occupied and empty room states. The ADA in every minute is defined as:

$$ADA(k) = \sum_{i=1}^{n}\left|P_{i+1}^{k} - P_{i}^{k}\right|, \tag{4}$$

where P_i^k denotes the i^{th} peak point of the Riemann integral in the k^{th} minute, and *n* is the total number of peak points in the k^{th} minute.

Additionally, adaptive threshold-setting based on a level-crossing algorithm was also used for the determination. Based on the signal's local maximum values, a threshold crossing was established and adaptively updated. If a point had a maximum value and was preceded by a value that was lower than the threshold, it was recognized as the maximum peak. Data was filtered after collection by the DAQ, and local maxima were computed and compared to a threshold for level crossings. The adaptive threshold was used to aid in accounting for changes in measurement equipment over time as well as temperature variations and other environmental factors. The baseline for the threshold was established via calibration at the beginning of the installation, and later adjusted based on the data average and standard deviation. In practice, this was basically a one-time set-up calibration that remained stable as long as the sensors were not swapped out or moved to a new location. However, the threshold could be reset for processing if an unusual change in the sensor performance or environmental noise were to be observed.

While the method used here to detect occupant presence works both for large-scale ambulatory motion and small-scale respiration and heartbeat motion, this particular use scenario involved hallway monitoring which was dominated by large-scale motion. A description of the use of this technology focused mainly on small-scale motion sensing, along with the extraction of heart and respiratory rates for sedentary subjects in the frequency domain, can be found in [18].

Once the radar dataset was collected, the signal was low-pass filtered with a 10-Hz cut-off frequency, as the motion of interest typically falls within this band. Median filtering was also used to remove the spikes that came from the SD-card current draw surge which occurred during the data writing. The average peak amplitude accumulation of the Riemann integral within a 30-second window was calculated, and if the value was greater than one or equal to zero, the system registered no presence of any occupants. If the value remained between zero and one, this indicated the presence of occupants.

The adaptive threshold value was initially set upon placement of the sensor and updated after the first data collection. For example, for one microwave occupancy sensor (labeled SWN) the threshold value was updated to 0.05 and this setting was used to accurately determine the presence of occupants for a period of almost eight months. Fig. 5 provides two examples of 8-hour data segments for data collected from two different sensors on two different days. The threshold for the data in Fig. 5(a) used a value of 0.05 to determine presence, while the data show in Fig. 5(b) used a value of 0.03.

III. INSTALLATION SITE INFORMATION

Six microwave occupancy sensors were placed in three wings on the fourth floor of Sakamaki Hall at the University of Hawai'i at Mānoa (UHM), a four-floor building with two atria and four wings on each floor. Each sensor was housed completely in a wall-outlet cover-box due to the strict limitations on form-factor and power supply imposed by the project.

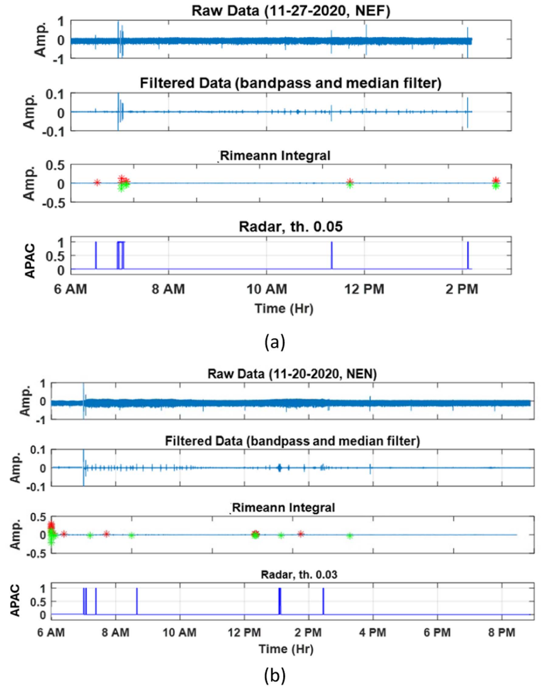


FIGURE 5. Recorded data for two different sensors (on different days) shown as (a) and (b). Raw data was low-pass filtered at 10 Hz, and a median filter was used to remove extraneous noise. The Riemann integral was calculated and peaks found (asterisk, red: positive, green: negative), and the amplitude difference accumulation (ADA) for a window of 30 seconds was used to determine occupant presence.

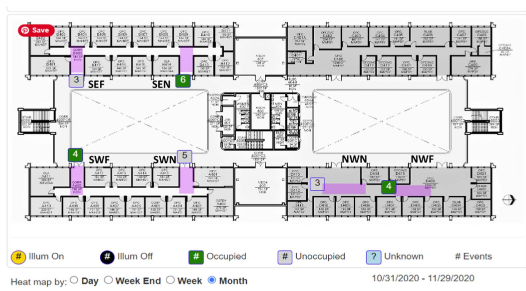


FIGURE 6. Sakamaki Hall fourth floor map. Purple areas indicate sensor placement.

Fortunately, the sensors used provide very wide coverage area and range even when used on floor level outlets, thus it was determined that the use of two sensors per wing would provide adequate coverage. The ground floor of Sakamaki Hall consists of classrooms, and the three floors above are offices used by several different departments. The locations are labeled as SWF, SEF, NEF, NEN, SEN, and SWN, indicating the Southeast, Southwest, and Northeast wings and nearer or farther from the elevator (Fig. 6). Sakamaki Hall has 4 wings per floor and an air handling unit (AHU) in each wing, for a total of 16AHUs. Each AHU is its own control zone.

The University of Hawai'i at Mānoa (UHM) has a chilled water system that uses water pipes to connect buildings to a central chiller plant, or "Anchor Plant." This system is called

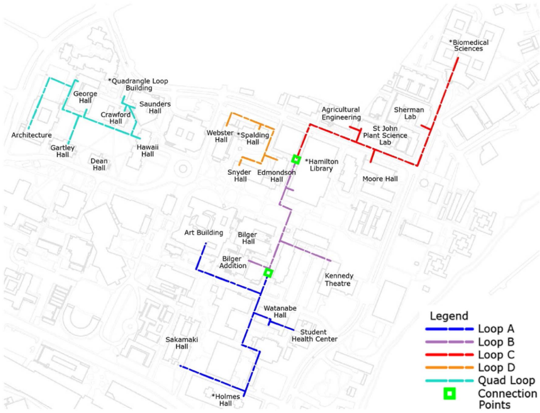


FIGURE 7. **Map of district cooling loop system at UH Manoa. Sakamaki Hall is on Loop A.**

a district cooling loop, and it offers an efficient way to provide heating and cooling to large facilities. The University of Hawai'i has four major district cooling loops on the Mānoa Campus. Sakamaki Hall is one of six buildings on cooling loop A, which uses chilled water from a plant in Holmes Hall, as illustrated in Fig. 7.

Hawai'ian Electric has deployed an energy data collection system within the Upper Campus of the University of Hawai'i at Mānoa. This system enables collection of data at the entry point for incoming electric power to eight buildings at the campus, one of which is Sakamaki Hall. The data is collected in 15-minute intervals including total building electrical energy usage (kWh) and power (kW). Sakamaki Hall's air conditioning uses a chiller plant that is shared with other buildings. The plant and chilled water loop electrical usage (kWh) and power (kW) as well as chilled water energy rate (tons) and chilled water usages (ton-Hrs) are collected at 15-minute intervals. The system also collects the chilled water energy rate in BTU for each building on the chilled water loop.

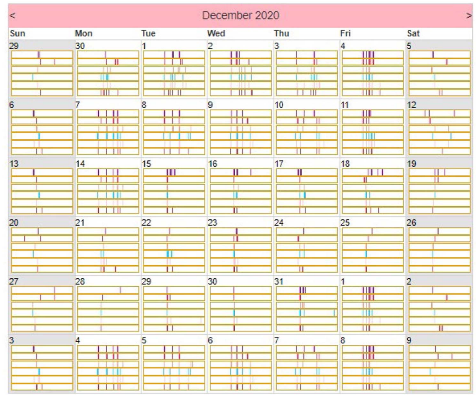
IV. RESULTS

A. WEEKEND VS. WEEKDAY OCCUPANCY DATA

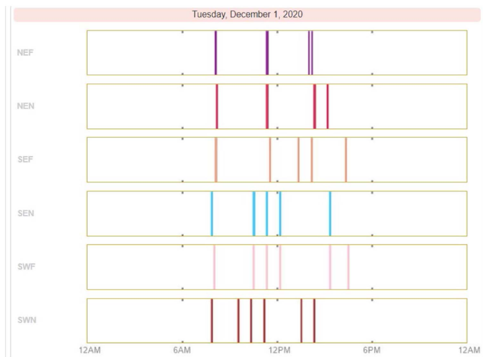
Occupancy data was collected over an 8-month period, and was stored and displayed on the data user interface. The heat map view in Fig. 6 shows the locations of the sensors, which areas were occupied, and displays the number of occupancy events for each sensor.

The calendar view shows the timeline for each sensor in a different row for each day, with a line representing each occupancy event (Fig. 8(a)). The user can click on a day to see that day's data with more detail (Fig. 8(b)). In the monthly calendar view, it becomes clear that occupancy is much greater on weekdays than it is on weekends.

To further analyze that, the comparative view offers the ability to select a time period and to look at the occupancy patterns on specific days, with user-selected bin sizes. In Fig. 9, week days (a) and weekend days (b) have been selected for

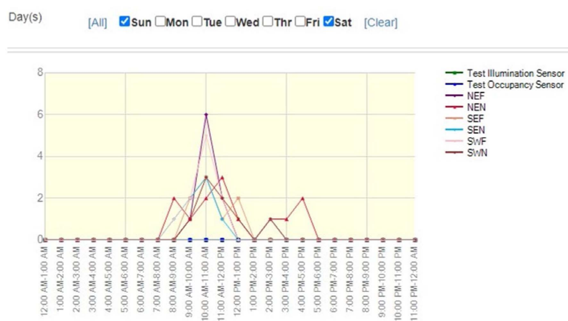


(a)

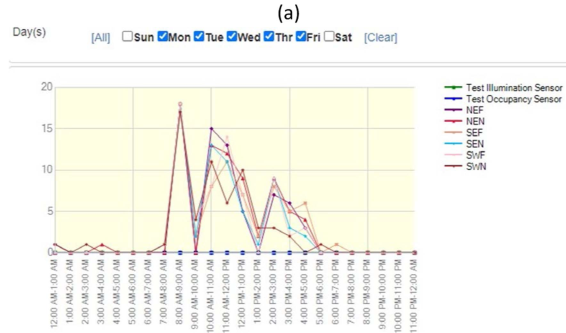


(b)

FIGURE 8. **Screenshots of data user interface calendar view of occupancy events, shown monthly (a) and daily (b).**



(a)



(b)

FIGURE 9. **Screenshots of data user interface comparative view for occupancy vents for on weekend (a) and one work week (b).**

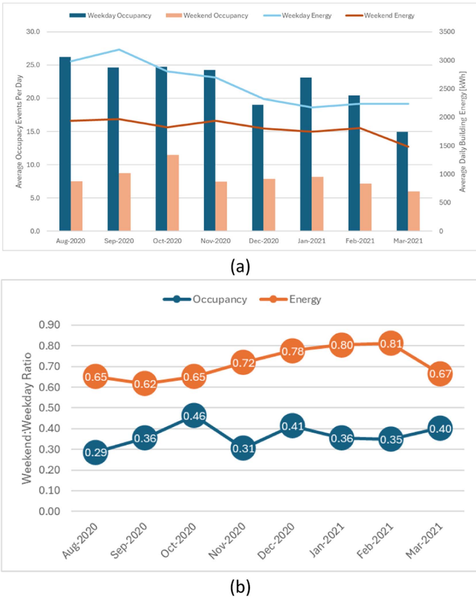


FIGURE 10. **Weekday and weekend energy and occupancy (a) and weekend to weekday ratio (b).**

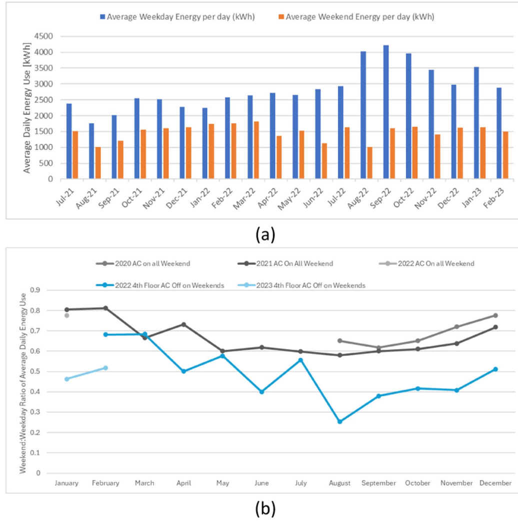


FIGURE 11. **Weekday and weekend energy consumption (a) and weekend to weekday energy consumption ratio (b).**

different views. Note that the y-axes auto-scale for each view and do not have the same scale between the two plots.

B. OCCUPANCY AND ENERGY CONSUMPTION DATA

The energy used by Sakamaki Hall at any time includes the incoming electric power to the building and a portion of the power used to chill water in Holmes Hall. Because the electricity information is provided in total KW on the electric meter readings every 15 minutes, the value is converted to kWh by multiplying the value by the number of hours, 0.25 to provide the number of kWh used in each 15-minute span. The chilled water usage data is provided in BTU for each building using the chilled water. The percentage of chilled water energy used by Sakamaki Hall was calculated as the amount used in Sakamaki Hall divided by the sum of the amount used in all the buildings cooled by that chilled water plant: Sakamaki Hall, Holmes Hall, Watanabe Hall, Marine Science Building, and Art Building. The chilled water energy use by Sakamaki Hall was calculated for each 15-minute interval as the chilled water energy use for the whole chilled water plant, multiplied by the percentage of the chilled water energy used by Sakamaki Hall.

The Sakamaki Hall building energy usage (other than the share of the chilled water energy) was calculated from the energy meter data (in kWh), by subtracting successive electric meter readings. Then the total Sakamaki Hall energy usage was calculated by adding this value to the share of the electricity from the chilled water plant that. The chilled water plant electricity was found to be about 50% of the total Sakamaki Hall energy consumption, bringing the HVAC portion to about 70% of the total energy. The University of Hawai'i at Mānoa Office of Sustainability was most interested in determining and adjusting the HVAC used based on the occupancy on weekends, so the energy usage was classified by weekday vs. weekend. Over various periods discussed in the results, the average daily energy usage was determined on weekdays and on weekends.

Fig. 10(a) plots both the average number of occupancy events per day on weekdays and weekends, and the average energy use per day on weekdays and weekends, for each month. Fig. 10(b) plots the ratio of the values from weekend:weekday over the months for which occupancy was measured. Although weekend occupancy events were about a third of those on weekdays, building energy consumption remained high, at 62–81% of weekday values.

C. ENERGY SAVINGS ESTIMATES

The University of Hawai'i at Mānoa Office of Sustainability made a decision based on the occupancy data, to turn off air conditioning on the weekends on the fourth floor of Sakamaki Hall, where the occupancy sensors had been installed. On February 10, 2022, the air conditioning was stopped on weekends in three of the wings on the 4th floor of the building (wings B, C, and D), totaling 10467 square feet. On August 12, 2022, Air Conditioning was turned back on for B wing. The energy used was analyzed for the periods from February 10 to August 11, 2022, and from August 13 to December 31, 2022. Fig. 11(a) shows the weekday and weekend energy consumption from July 2021 through February 2023.

Because the original occupancy analysis was performed in 2021, when occupancy and energy usage was lower due to COVID restrictions, and modifications to the HVAC schedule were made in 2022 when occupancy was more typical, and because variations in weather impact daily HVAC energy usage, we also looked into the weekend: weekday ratio of energy consumption.

Fig. 11(b) shows the ratio of weekend:weekday energy consumption by month from August 2020 through February

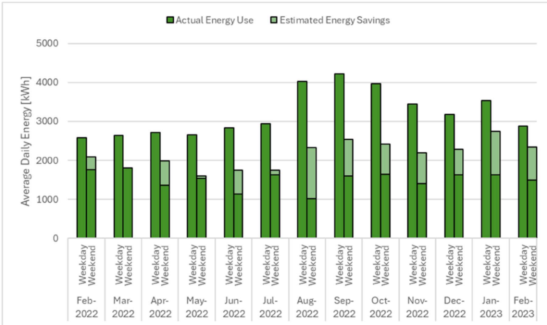


FIGURE 12. **Weekday and weekend average daily energy consumption. Light green indicates energy savings.**

2023, with the values obtained while the air conditioning was turned on shown in shades of gray, and values obtained when at least some wings of the 4th floor had air conditioning turned off on weekends in shades of blue. Note that although Fig. 11 shows that the absolute levels of energy consumption on weekends did not drop significantly following the air conditioning being turned off, the ratio of weekend:weekday energy consumption had a significant drop. Seasonal variation in the weekend:weekday ratio of energy consumption can also be seen in this data.

Because of the seasonal variation in building usage and HVAC needs, and because of the year-to-year variation in building occupancy during the COVID epidemic, energy savings were estimated by determining what weekend energy usage would have been had the ratio of weekend:weekday energy usage remained the same as it was prior to HVAC schedule modification, and then subtracting the actual weekend energy usage from that number over the same date range. For each month the previous year's weekend: weekday energy ratio was multiplied by the average weekday energy consumption during that month, to provide an estimate of weekend energy consumption had the HVAC change not been implemented. The actual average daily energy consumption on weekdays and weekends and the estimated daily weekend energy savings is plotted in Fig. 12.

To estimate the total annual energy savings, for each month, the average daily weekend energy savings was multiplied by the number of weekend days, and these were summed from March 2022 to February 2023, providing a total estimated annual savings of 65,787 kWh. Sakamaki Hall was 47319 square feet of conditioned space, so the annual energy savings is 1.29 kWh/sf.

Wings B-D of the 4th floor of Sakamaki Hall are comprised of 10467 square feet, so this is an estimated savings of 6.3 kWh/sf/year. In Hawai'i, electricity cost is about \$0.39/kWh, so this provides an annual savings of \$2.45/square foot, or a total cost savings of \$25657 for wings B-D, and is projected to save \$115931 annually for the whole building.

In 2022, the building's total energy use was 970,242 kWh. Thus, the annual energy usage is 21.1 kWh/sf of conditioned space. We estimate that the energy saved is approximately 6% of what we estimate that the annual usage for wings B-D would have been without savings, and about 20% for the whole building.

V. CONCLUSION

Improving energy efficiency is a critical strategy for addressing climate change. Microwave occupancy sensors for HVAC control are a promising approach for improving energy efficiency. This paper presented the application of a microwave occupancy sensing system for the monitoring of occupancy patterns at an office building on University of Hawai'i at Mānoa campus over a period of eight months. Occupancy data was used to inform HVAC scheduling, and it was demonstrated that as a result of scheduling changes overall building energy consumption was reduced by about 20%. In buildings like Sakamaki Hall, where HVAC accounts for over 70% of energy use, even modest reductions in HVAC operation can results in significant energy savings, which is critical for controlling climate change.

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