Building Technologies & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

A low-cost centralized HVAC control system solution for energy savings, load shedding, and improved maintenance

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Energy Technologies Area
August 2022

Fauchier-Magnan N., Morejohn J., Pritoni M. (2022). A low-cost centralized HVAC control system solution for energy savings, load shedding, and improved maintenance. ACEEE Summer Study on Energy Efficiency in Buildings 2022. https://doi.org/10.20357/B74608

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the US Department of Energy under Contract No. DE-AC02-05CH11231.

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ABSTRACT

University campuses rely on centralized controls for managing and optimizing complex HVAC systems in larger buildings. However, most campuses also have many smaller buildings with packaged HVAC systems controlled by a stand-alone thermostat. Even when these distributed and often overlooked systems have modern programmable thermostats, they cannot be centrally monitored or controlled, and they are typically not programmed adequately.

This paper describes the implementation of a low-cost centralized control solution for these systems serving smaller campus buildings, mostly under 5,000 sf and representative of light commercial spaces. Thanks to advances in technology spurred by residential and commercial IoT developments, simple networked thermostat solutions exist that can easily replace original thermostats, and, connect these systems to a web-based portal for monitoring and control. We show that, with small customizations, these platforms can be integrated into facility management workflows. Beyond the energy savings potential from improved scheduling and closer management of these systems, there are significant advantages for maintenance crews since these systems can now be monitored on smart phones or tablets. A grid-responsive load-shedding program has also been implemented for additional cost savings. The networked thermostats can also be connected to additional systems such as economizer controls for improved ventilation management and energy savings. With data from these systems integrated centrally, it can also be used for improved analytics and fault detection.

A toolkit has been developed to share the program with other campuses, whether for energy savings, improved management of ventilation, or a more proactive maintenance approach.

Introduction

Most large commercial buildings in the US with built-up (i.e., custom) Heating Cooling and Ventilation (HVAC) systems rely on building automation systems (BAS) (EIA 2018). The use of a centralized system is particularly important in university campuses, where unified monitoring and control of these systems is essential to effectively coordinate maintenance and engineering staff (Armstrong et al. 2000; APPA 2022). While several definitions exist, BASs are often described as “centralized, interlinked, networks of hardware and software, which monitor and control the environment in commercial, industrial, and institutional facilities” (ASHRAE, 2015). BAS technology first emerged in the ‘70s and was further developed in ‘80s-90s, targeting large and complex commercial building systems and enabling control over HVAC, lighting, security and fire systems (Wong & So, 1997). Modern BAS hardware uses microprocessors, embedded in field devices/controllers and supervisory computerized systems, to coordinate the distributed hardware. The technology is mature and reliable, but not costeffective for small-medium buildings with simple HVAC systems, such as packaged rooftop units (Katipamula, 2012).

As a result, small buildings have historically been controlled using stand-alone thermostats, that are less complex and less expensive than BASs. Sometimes these thermostats have simple programmable features and allow to set a schedule, that needs to be entered manually by a user. However, in practice, they are often programmed incorrectly. Further, when a building has multiple packaged units, they are not generally coordinated: the setpoints and the schedules configured in each thermostat are not synchronized with each other (Katipamula, 2012). These issues cause energy waste, uncomfortable working conditions and difficulty in performing timely maintenance. For a university campus, lack of centralized reporting and control capabilities is a significant problem because facility management has the responsibility to provide comfortable environment and save energy, but has no visibility into the operation of these systems.

In the last two decades, several Internet of Things (IoT) technologies have flooded the consumer electronics market, mostly targeting smart home applications (Ford et al., 2017). In particular, smart thermostats have become very popular devices for home owners and have been enthusiastically supported by utility programs (Robinson et al., 2016). These thermostats are characterized by intuitive and remote (mobile and web) interfaces, Internet connectivity, and improved intelligence (e.g., occupancy sensors, energy efficient algorithms, adaptive behavior). More recently, some of these technologies have been adapted for the light commercial building sector and we have started to see increased adoption (Rovito et al., 2014). However, these technologies are not necessarily designed for the needs of large campuses that have: 1) hundreds of buildings in their portfolio 2) strict security requirements (Graveto et al., 2022), 3) existing workflows for building management and maintenance.

This paper describes the design and implementation of a low-cost centralized control solution for small campus buildings, mostly under 5,000 sf, with simple rooftop HVAC systems. The solution uses commercial smart thermostats and integrates them with facility management tools and workflows. We show the benefits obtained for the deployment of the platform on over 100 buildings and share the tools developed for our custom integration. We believe this solution can be easily replicated by other campuses and large organizations.

Motivation and Technology Requirements

The University of California, Davis (UC Davis) campus is located in Davis, California, with over 1,000 buildings and 12M square feet and hosts more than 30,000 undergraduate students, ranking #2 in student population in the University of California system. The energy and engineering[1] (E&E) team provides engineering support to the campus facilities shops, develops and manages campus energy projects and the centralized HVAC control system. They also build web tools and educational sites for engaging building occupants. In the last 5 years, the E&E team has developed a robust energy efficiency program that has saved the campus over $5M, with projects mostly focusing on large laboratory buildings. While the program has been very successful, it has not addressed a large portion of the building stock, namely the hundreds of

[1] https://facilities.ucdavis.edu/energy-engineering

small commercial buildings with no building automation system spread across the 5,300-acre campus.

After evaluating a few technology vendors, the E&E team realized that most product offerings did not meet IT security standards nor they did easily integrate with existing energy management workflows. For these reasons the team defined a set of technology requirements and conducted a market review of existing controls for small buildings with packaged units to identify suitable technology candidates. We present these essential and value-adding features below, followed by the rationale for their inclusion.

- Essential features:
  - **Centralized scheduling:** one main goal with this project was to improve HVAC schedules to save energy. We needed the ability to centrally and remotely view and adjust schedules, setpoints and thermostat configuration, with flexibility for building occupants to adjust as needed.
  - **Scalability**: we needed one solution that would be able to connect to the hundreds of small HVAC systems that we have on our campus.
  - **Cost-effectiveness:** because the energy consumption and savings potential of small buildings is lower than that of larger buildings, we needed a solution whose first cost would be lower than traditional Building Automation Systems (BAS).
  - **Simplicity:** the solution had to be simple to install, configure, and adapted to the relative simplicity of small HVAC units. A device with output relays controlling the HVAC unit's fan, heating system and cooling system was sufficient for our needs.
  - **User-friendliness:** to be successfully adopted, the solution needed to have an intuitive interface for occupants, technicians, building managers and engineers.
  - **Historical trend access:** maintenance technicians need the ability to easily view historical operating data from the HVAC systems so they can better troubleshoot issues that arise.
  - **Cybersecurity:** due to cybersecurity concerns from the UC Davis IT network managers, our solution could not rely on the campus wi-fi network for its communications.
- Optional, value-adding features:
  - **Mobile-friendly** user interface, both for maintenance technicians and building occupants.
  - **Remote screen lock:** ability to prevent adjustments at the front screens for thermostats placed in public spaces (eg classrooms), either permanently or during certain periods.
  - **Open Application Programming Interface (API)**: possibility of programmatically integrating thermostat time-series data with external sources, to conduct data analysis in other platforms (e.g., fault detection and diagnostic tool).
  - **Accessories**: option to add remote temperature sensors, to include a CO_2 or humidity sensor in the thermostat, to add an economizer controller to the HVAC system, or to control other loads (e.g., exhaust fans, outdoor lights).

The team reviewed more than a dozen products and selected a technology: the Pelican Wireless Thermostat[2] that met all the important criteria, as described in Table 1.

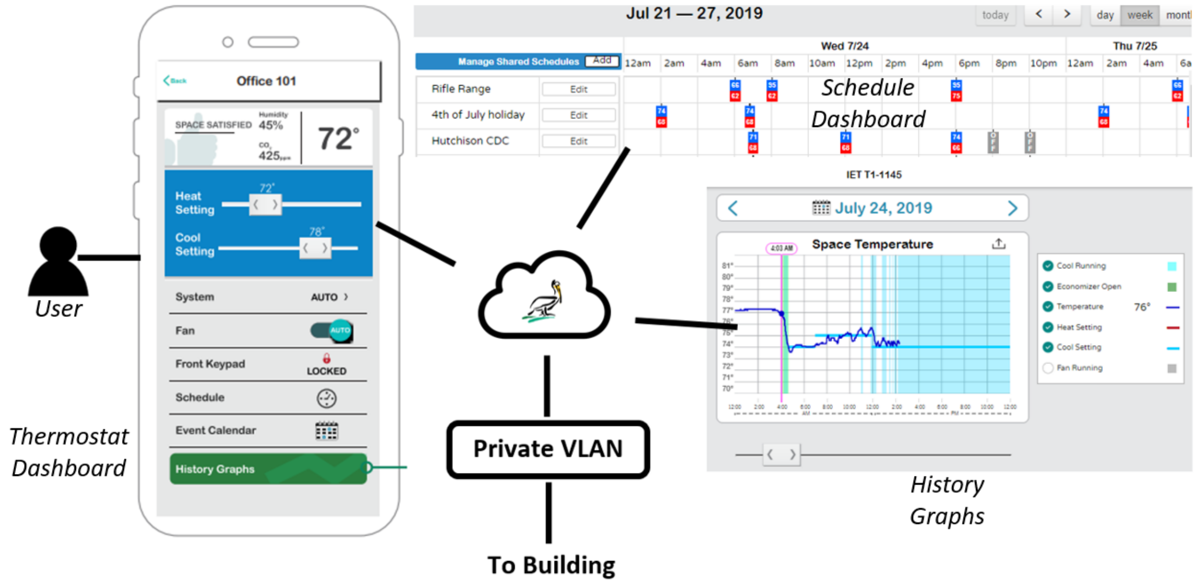
Table 1: Features of the selected technology and fulfilment of the requirements

Feature	**How the selected solution fulfils the requirements**
1. Essential features	
Centralized scheduling	Offers a web-based central scheduling interface where each HVAC system or groups of systems can receive a dedicated schedule (Figure 1). Flexibility for building managers to create one-time schedules for special events.
Scalability	The selected technology is designed to provide access to hundreds of thermostats through one central interface.
Cost-effectiveness	The selected technology uses a small number of very affordable components. Installing the technology in an 'average' small building with 4 HVAC units costs less than $3,000 in materials and labor. The largest cost is for installing and connecting the building-level gateway.
Simplicity	The selected technology is quick to install and configure. Thermostats are simple replacements of existing 24V thermostats and can be configured in the field via tablet or smartphone, in about one hour per unit.
User-friendliness	The web-based interface is easy to use and intuitive (Figure 1). Building managers can be given access to their building only so they can easily find the systems they need without scrolling through the whole portfolio.
Historical trend access	Service technicians and engineers can easily view historical operating data from the units (e.g., heating, cooling and fan status, room temperature), other inputs when available (e.g., room CO2 and humidity level, discharge air temperature). Figure 1 presents a few screenshots of the mobile interface.
Cybersecurity	The thermostats form a mesh network and connect to a single gateway per building or per cluster of buildings. The gateway then connects to the internet via a wired connection (ethernet). Network managers can set strict firewall rules on these ethernet connections (Figure 2)
2. Optional, value-adding features	
Mobile-friendly	All screens in the user interface have a narrow design to easily fit on a smartphone
Remote screen lock	The thermostats' front keypads can be "locked" (i.e., occupants cannot make adjustments at the keypad) through the central interface.
Open API	A well-documented web API can be used to bring data into other platforms.

[2] https://www.pelicanwireless.com/

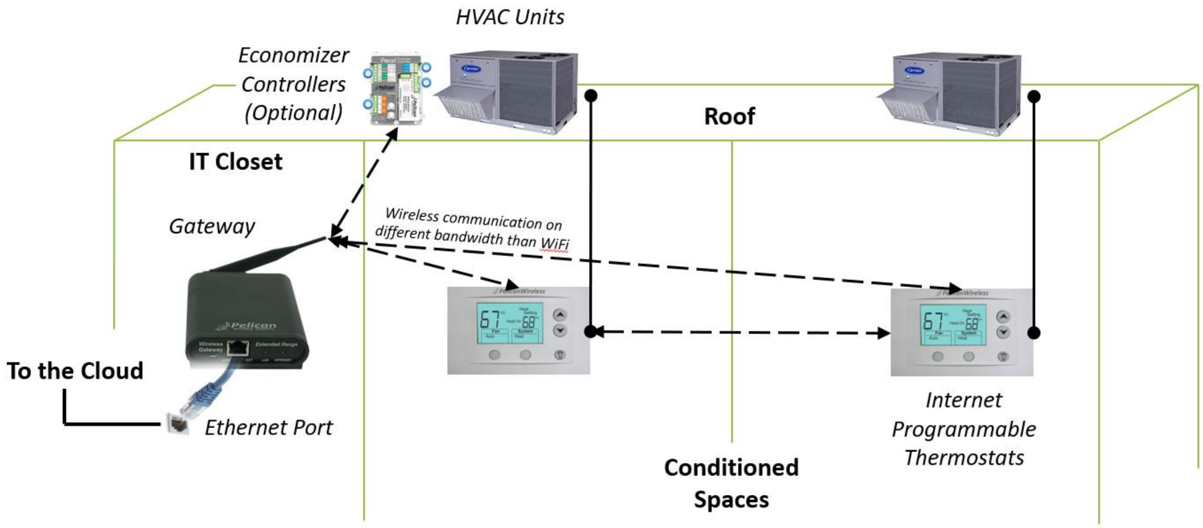
Accessories	The solution can also control economizers and can enable / disable 120V loads on a schedule (e.g., outdoor lighting, bathroom exhaust fans).

Figure 1 illustrates some of the interface screens available via the vendor cloud and Figure 2 depicts the network infrastructure and hardware needed in a small commercial building.



Source: Adapted from Pelican Wireless documentation

Figure 1: Web and mobile interface screens for the selected technology available from the vendor cloud (left: single thermostat settings, top: scheduling dashboard, right: runtime and temperature historical graphs)



Source: Adapted from Pelican Wireless documentation

Figure 2: Network architecture and hardware needed in each building

Technology Deployment

As of March 2022, the selected technology was installed in 101 buildings on the main UC Davis campus, covering a floor area of about 500k sf. 12 of these buildings have dedicated energy meters. The thermostat API was also used to transfer the data generated by the devices into the campus data warehouse and into the fault detection and diagnostic platform. The setup of scheduling, setpoints and grid-response are discussed below.

Centralized scheduling

The centralized thermostat interface gives the ability to set appropriate schedules that match occupancy, and to maintain those schedules over time. For our project, we engaged building occupants early on in the process, and set HVAC schedules based on the occupancy schedules defined by the occupants. We used built-in optimal start algorithms to optimize start-up times, based on weather. We set up recurring schedules only for regular occupancy; to handle occasional occupancy such as weekend events and after-hours occupancy, we relied on occupants to use the thermostats' override function. We also gave building managers access to their thermostats through the web application, where they can set up one-time events when needed. In addition, we used the API along with a custom Python script to centrally adjust HVAC unit schedules on university holidays (about 10 days per year). Occupants were informed by email 1 week before each holiday and were able to opt out of the HVAC 'holiday shutdown'.

Setpoint management

We set heating and cooling setpoints based on UC Davis campus standards (68 º F heating, 74 ºF cooling), and centrally programmed the thermostats. We also allowed occupants to make manual adjustments at the thermostat within specific boundaries: cooling (respectively heating) setpoints may be manually adjusted down to 68 º F (up to 74 º F). These manual adjustments are temporary and are re-set to the default values each day; occupants wishing to make permanent setpoint adjustments may contact their building manager or Facilities Management to request so. Research has shown that occupants feel more comfortable in their space when they have some level of control over HVAC systems (Luo et al. 2016; Wagner et al. 2007).

Grid responsiveness

Since the web-enabled thermostats provide remote temperature setpoint management, they can be used to participate in demand response (DR) programs. During a DR event, we were able use a special function in the central interface to increase all thermostat setpoints by an adjustable setpoint. In concert with building occupants, we found that 3 ºF was an acceptable value for this temperature adjustment. Some critical buildings were opted out permanently from this function. For instance, the campus telecommunications building houses critical equipment and was not included in the DR program.

Testing and Evaluation Method

We installed the thermostats between 2019 and 2022. The data was extracted using the API and added to our campus data warehouse.

Energy Savings

For the subset of buildings that have energy meters installed, we performed measurement & verification (M&V) following the International Performance Measurement and Verification Protocol (PIMVP), option C - whole facility - (Cowan, 2002). Three metered buildings were discarded, because we were unable to obtain acceptable baseline energy models ($R^2 \geq 0.70$, CVRMSE ≤ 0.30). The remaining 8 buildings represent 89,000 sf of conditioned area, or 18% of the total 494,000 sf of conditioned area controlled by web-enabled thermostats on the UC Davis campus. For each building, the baseline period is a 12-month period preceding the installation of the web-enabled thermostats in that building. We used multi-linear regressions to develop the baseline models; independent variables for these models include heating-degree days, cooling-degree days, and day of week. Electricity consumption in these buildings is heavily influenced by outside air temperatures, resulting in models with high coefficients of determination (R^2, typically above 0.90, see Table 2 in the Results section). The post-project period is the 7-month period from September 2021 (when campus went back to full operations) to March 2022 (when this paper was written). Savings were extrapolated from this 7-month period to average annual savings by using the ratio of heating- (respectively cooling-) degree days in a typical year (based on typical meteorological year (TMY3) data), to the number of heating- (resp. cooling-) degree days during the 7-month period.

Demand Flexibility

During the summer of 2021, we also tested the demand response capability of this technology, during several peak days. M&V was performed using a system isolation approach, IPMVP option A (Cowan, 2002). Because the majority of the small buildings included in this program do not have building electricity meters, we used a 'virtual' energy meter for each HVAC unit based on the on/off status of the compressor and the unit's design cooling capacity, along with an estimated Energy Efficiency Ratio (EER) of 12.0 Btu/Wh. We then aggregated these individual meters to one overall 'virtual meter' for all controlled HVAC systems in campus. For each demand response event, we used a baseline period corresponding to a 1-week period adjacent to the event, excluding weekend days and university holidays; all the baseline models were acceptable ($R^2 \geq 0.70$, CVRMSE ≤ 0.30). We calculated the highest demand reduction observed over 1-hour periods and the mean hourly demand reduction observed during each event.

To have a complete picture of the benefits of the technology, we discuss the feedback from occupants, operators and energy managers at the end of the Results section below.

Results

Energy Savings

Table 2 below presents the results of the M&V process. The median energy savings were 16.1 kBtu/ft^2/yr or 28% of baseline, for electricity and gas combined, with a standard deviation of 13.0 kBtu/ft^2/yr or 18% of baseline. In most cases, web-enabled thermostats bring a measurable reduction in energy consumption. However, there is significant variability in energy savings among the modeled buildings. This reflects the many factors that influence energy savings, including pre-project conditions (especially how occupants interacted with the existing thermostats), the quality of the building's envelope, the efficiency of the HVAC systems, and whether economizers were added. For instance, building B is a staff learning center that had poorly-programmed thermostats before the project; the new thermostats have allowed building staff to reduce equipment schedules to closely match training schedules, dramatically decreasing HVAC unit runtimes. On the other hand, building C, which is a childcare center, showed a slight increase in energy consumption; this is because its pre-existing thermostats were well-managed by staff, and the new thermostats provided staff with even more control and ability to modulate comfort at the expense of additional energy use. Detailed results for building C show electricity savings thanks to the addition of economizers, and a slight increase in gas consumption likely due to slightly higher heating setpoints than those previously used.

Table 2: Energy Savings Results at Modeled Buildings

Building Name	Building Function	Electricity model metrics		Natural gas model metrics		Total savings (Electricity + Natural gas) (kBtu/ft^2/yr)	Percent Energy Savings
		R^2	CVRMSE	R^2	CVRMSE		
A	Childcare center	0.97	0.12	0.97	0.22	30.15	41%
B	Office	0.96	0.07	0.93	0.58	32.92	52%
C	Childcare center	0.98	0.06	0.99	0.15	-0.59	-2%
D (*)	Office	0.97	0.04	n/a	n/a	20.98	29%
E (*)	Office and lab	0.96	0.07	n/a	n/a	11.20	26%
F (*)	Office	0.93	0.05	n/a	n/a	11.12	31%
G	Office and locker rooms	0.95	0.04	0.97	0.21	27.64	11%
H (*)	Office and locker rooms	0.88	0.13	n/a	n/a	9.20	18%
Overall						Median: 16.1 Stdev: 13.0	Median: 28% Stdev: 18%

(*) These are all-electric buildings with no gas service.

Based on the numbers above and extrapolating to the whole surface controlled by web-enabled thermostats on the UCD campus, the project is estimated to save about $80,000 per year in energy costs[3]; the total investment in the system is estimated around $200,000 including labor and materials, or about $2,000 per building on average, resulting in a simple payback under 3 years for this project.

Demand Flexibility

For each of the 8 event dates (each spanning over 2 to 6 hours), we computed the maximum and the mean demand reduction for the aggregated demand of the buildings with thermostats, calculated over 1-hour time steps. We then computed the median values for the maximum and the mean demand reduction over the 8 event days. The median of the peak

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are $0.076 / kWh for electricity and $0.775 / therm for gas demand reduction was 91.5 kW and the median of the mean demand reduction was 31.5 kW (see Table 3 below). The peak and mean demand reduction represent about 10% and 4% of the total HVAC-related peak demand from buildings controlled by web-enabled thermostats; this is significant enough to be measurable, and can help reduce strain on the grid during extreme weather days.

Table 3- Demand reduction results during demand response events

Event date and time	Maximum Demand Reduction	Mean Demand Reduction	Baseline Period	Baseline model metrics	
				R^2	CVRMSE
Jun 01 2021, 6-8 pm	100 kW	46 kW	Jun 18 – 24, 2021	0.93	0.16
Jun 15 2021, 6-8 pm	83 kW	43 kW	Jun 18 – 24, 2021	0.93	0.16
Jun 17 2021, 5-8 pm	80 kW	29 kW	Jun 18 – 24, 2021	0.93	0.16
Jul 12 2021, 6-9 pm	45 kW	-4 kW	Jul 1 – 11, 2021	0.95	0.17
Jul 28 2021, 4-8 pm	16 kW	-3 kW	Jul 13 – 27, 2021	0.96	0.15
Jul 30 2021, 3-9 pm	111 kW	34 kW	Jul 13 – 27, 2021	0.96	0.15
Sep 08 2021, 4-9 pm	150 kW	49 kW	Aug 24 – Sep 7, 2021	0.95	0.20
Sep 09 2021, 4-9 pm	164 kW	9 kW	Aug 24 – Sep 7, 2021	0.95	0.20
Median	91.5 kW	31.5 kW			
Standard Deviation	49.5 kW	21.8 kW			

Additional Benefits

Reliable economizer controls and ventilation

With the selected technology, economizer controllers can be installed on small packaged units and integrated with the same platform. The networked thermostats can also be installed with a native CO2 sensor, enabling demand-controlled ventilation. Overall, this can reduce compressor runtimes and cooling energy consumption by using the economizer when a space needs cooling on a mild day; this also greatly improves ventilation management and air quality, which is otherwise problematic in small buildings with typical HVAC systems and controls (Pistochini et al. 2020). The economizer controllers also provide automated fault detection (compliant with Title 24 requirements (CEC, 2019)) and send alerts to facilities managers and maintenance technicians when a failure is detected. This gives maintenance technicians the confidence that the economizers will remain reliable over time, and won't cause unexpected comfort issues.

Remote visibility for Maintenance

Web-enabled thermostats offer additional benefits, including remote visibility and controls for maintenance technicians. The thermostats they replaced provided local controls only and offered no remote visibility. For any trouble calls that came in for these systems, maintenance technicians would have to drive out to the site to visually inspect the system and its controls. More importantly, the lack of visibility meant that many equipment issues went unaddressed until the system failed completely and the occupants finally noticed and were forced to call for help. But the new technology allows for remote access to the controls, and an additional layer of fault diagnostics to alert technicians to potential problems, like when a compressor is running but the temperature continues to increase, or a system fails to start up on its schedule. Engineers and technicians can not only view the systems remotely, including both real-time and historical data, but they can also manage the systems through remote controls to change schedules or setpoints, without a site visit required.

In the example shown in Figure 3-4 below, a technician had received an alert that a unit had failed, and they used the historical trend data to diagnose the issue with the failed HVAC system. The trend data shows that the heat is continuously commanded to run starting around 2:00pm on November 1st (indicated by the light red background in Figure 3 below), but the space temperature (blue line) continues to decrease and the supply temperature from the unit (green line in second graph below) indicates that the furnace is not operating. In this instance, the technician was able to identify that the ignition module had become stuck; on November 2nd, about 12 hours after the unit's ignition had failed, he was able to remotely reset the ignition module through the online interface, which allowed the unit to run again. The space was comfortable again in a very short amount of time, and a field technician was then sent out to replace the ignition module to prevent another defect.

Improved occupant satisfaction

While the web-enabled thermostats allow for remote visibility and control, they also allow facilities teams to grant building occupants greater freedom to control their own space temperature, because system schedules and setpoints can be reset or reviewed remotely. As was mentioned above, occupant comfort improves with improved controllability of environmental factors (Luo et al. 2016; Wagner et al. 2007). Facilities teams can also grant building occupants or building managers remote access to their own building's HVAC controls, which allows them to adjust their system from their own phone or workstation.

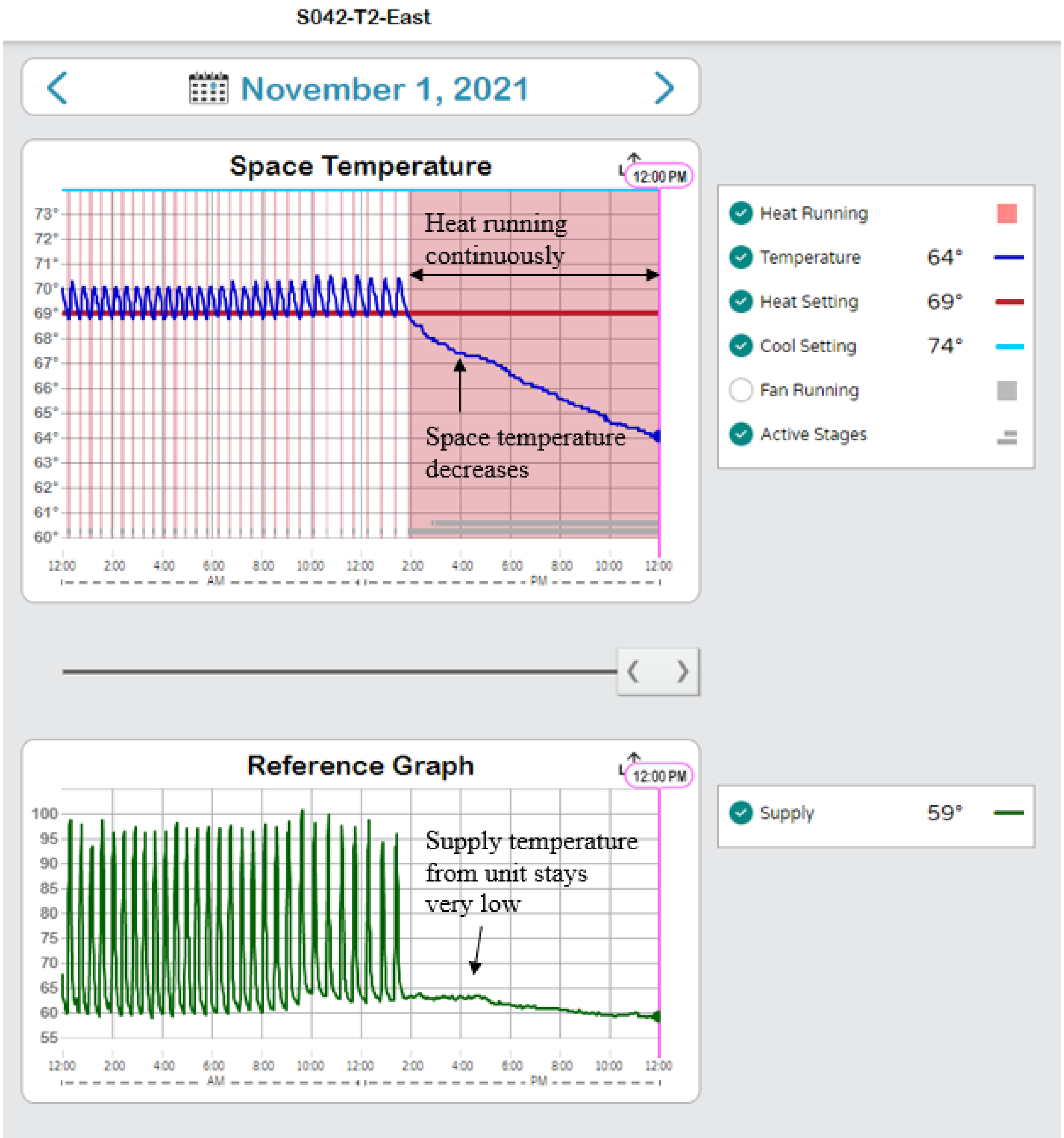

Figure 3 – Sample Trend Data used by UC Davis HVAC Technician to remotely troubleshoot field issues. Top panel: thermostat calling for heating but temperature dropping; Bottom panel: supply temperature stays very low.

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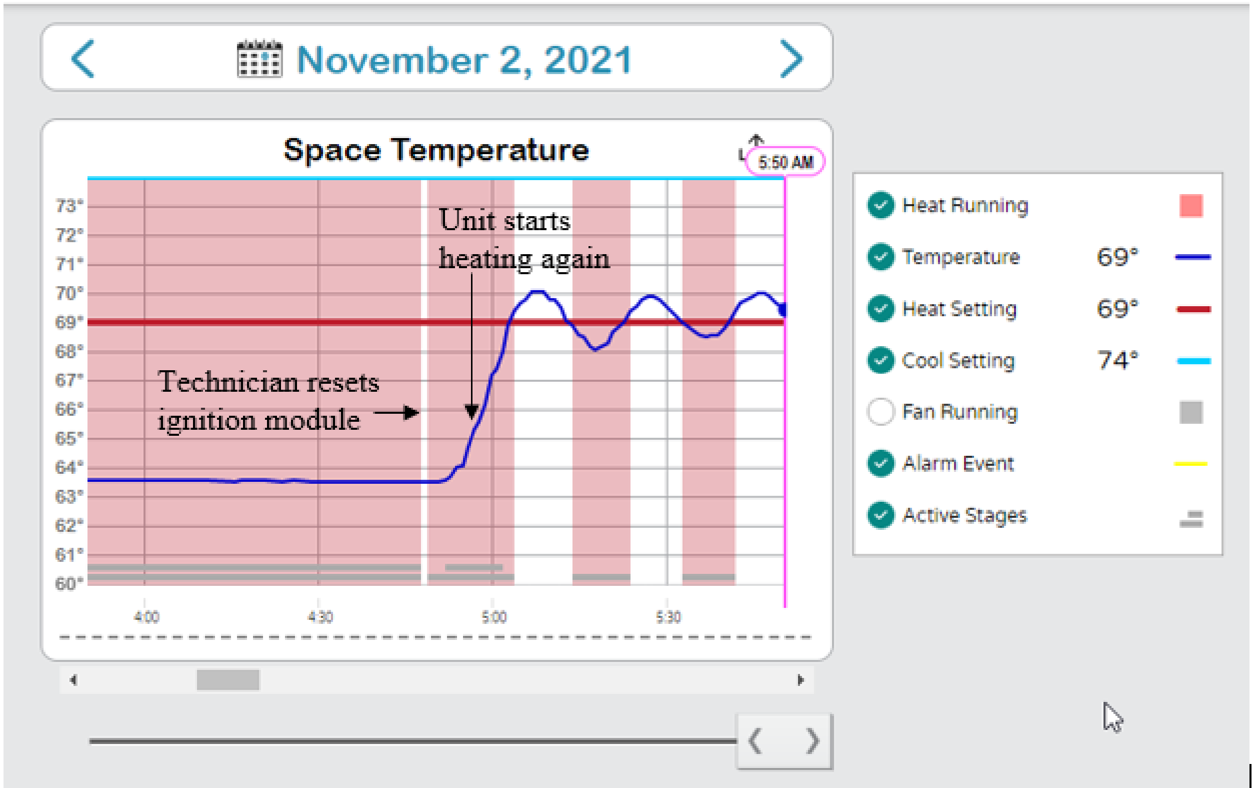

Full video can be viewed at this link: https://youtu.be/FXaq8exqHs8

Figure 4 – Sample Trend Data used by UC Davis HVAC Technician to remotely troubleshoot field issues. After the unit is restarted the space temperature returns in comfortable range.

Discussion and Conclusion

In summary, for a relatively low cost, smaller commercial buildings that would typically have only local controls can be retrofit or designed with a centralized control system that offers many benefits to the maintenance teams and the building occupants. At the UC Davis campus, installed costs for web-enabled thermostats are about $3,000 per building (for an 'average' small building with 4 packaged HVAC units).

Data analysis has found significant energy savings, with median savings amounting to 28% of overall building energy use. The web-enabled thermostats can also help reduce electrical demand, although the amount of available demand reduction potential is somewhat limited: data show that demand was only reduced by 4% on average during demand response events.

Maintenance staff are able to remotely troubleshoot operational issues with the HVAC units and can take appropriate action to quickly address these issues. Occupants benefit from spaces that are more comfortable when they are present, and they can have some level of control over the temperature settings – within boundaries set by the campus maintenance staff.

Other campuses, owners, portfolio managers and others who would like more information on this program, including suggestions for how to start a similar program for their properties, can download the toolkit that UC Davis developed for other University of California campuses. The toolkit includes presentations and resources for energy managers, building occupants, HVAC technicians, and IT teams. It can be downloaded at https://app.box.com/s/5xeq69l39sg33jchza0x60cnskgfnxwe

Acknowledgments

We want to thank our UC Davis Facilities staff Nate Cardoza and Tom Ryan who have championed and implemented this project at scale; UC Davis undergraduate and graduate students who have helped develop this project over the last 4 years (including Abe McKay, Devon Schmidt, Rhys Davis, Tanner Palmer, Tomoya Otsuka, Eunbee Park, and Dominic Stephen); and our UC Davis Facilities data scientist Daniel Colvin who helped to prepare the quantitative results presented in this paper.

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