

## Using Campus Energy System Data to Save Energy and Provide Students with Real-world Learning Experiences

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## **Abstract**

A variety of engineering classes teach students how to analyze thermodynamic systems or even provide students with training on simplified lab models of real systems. However, relatively few courses provide students with exposure to actual thermodynamic systems in operation. Additionally, campuses and large building complexes often have an abundance of operational HVAC systems and energy usage data, but comparatively few resources to analyze and monitor their performance. Recognizing this need and opportunity, we worked with the facilities department at our institution to use the campus energy operations as a source for student projects in multiple departments and at both undergraduate and graduate levels. These projects included monitoring HVAC operations to identify system faults, interpreting HVAC control logic to identify zero-cost energy savings, quantifying the potential benefit of energy efficiency retrofits in campus buildings, using campus energy load profiles to design alternative power solutions, and analyzing multiple data sets to determine strategies for reducing peak electricity demand.

These projects gave students a deeper understanding of thermodynamic systems, going beyond the schematics they learn in textbooks and homework problems, while also teaching them about the practical operational and engineering challenges associated with real-world energy-consuming devices. Simultaneously, the identification of faults and energy efficiency opportunities enabled significant energy savings opportunities for the university. Such educational strategies can extend to almost any university, and can embed within existing courses or be developed for specific building science or informatics courses. These projects can engage students from a variety of disciplines, including computer science, mechanical engineering, and sustainability-focused programs, and they create opportunities for interdisciplinary problem solving.

## **Introduction**

Energy education can be found in many disciplines throughout a college curriculum. The basic laws of the conservation of energy and an introduction to its many forms is integral to first-year physics coursework. Early environmental science courses emphasize the impacts of energy extraction and conversion on natural systems. Later courses in environmental studies explore natural resources used to harvest energy. Business schools offer courses in the areas of energy and environmental economics. Traditional engineering disciplines study energy transformation, and generate specialized courses tied to traditional and emerging energy systems, including renewable energy systems as well as energy resource management. Given the ubiquity of energy-focused courses on a college campus, it is convenient to use the real-live energy systems of the

campus itself to emphasize concepts learned in the class - using the campus as a living laboratory.

A living laboratory is considered a real-world system that can be observed and manipulated by the user to drive improvement and innovation [1, 2]. The concept first emerged within the field of computing and information technology. Within the University setting, the concept began to strongly unfold in the context of sustainability education. Some of the key features of living laboratories are that they are working systems that involve the user of the design. In a college setting, the users are the students, faculty, staff and even the surrounding community. Another important feature of living lab activity is the participation from multiple stakeholders. In the case of a college campus, getting participation from both faculty and facility service personnel is critical for positive student project outcomes, like identifying a feasible operational change that results in lower energy loads.

The living lab approach has worked well to integrate sustainability topics into induction-based or project-based learning opportunities in the classroom [3, 4, 5, 6, 7]. The University of Manchester created a University Living Lab initiative that features a website with an inventory of sustainability/energy-based projects that groups of students can take on as part of classroom projects, graduate theses/dissertations or tackle as an extracurricular activity. The pipeline of projects is generated by a mix of stakeholders that includes faculty, facilities, and local industrial operations in the neighboring community. Projects that students engaged in ranged from building retrofits to new campus development activities and supply chain innovation to help with campus management decision making [6]. Duke University features a similar approach. Their website showcases areas on campus that have been manipulated to better improve the sustainability of campus operations, and they link these efforts to global sustainability issues [7]. Further, the 'Duke Campus as a Laboratory' initiative offers a funding platform to allow students to run experiments and test ideas on campus that promote sustainable solutions.

The work described here provides explicit examples by which our university has leveraged its live campus energy and metering systems as learning tools to teach sustainability and energy concepts within the classroom. The examples span the disciplines of mechanical engineering, engineering design, and environmental/climate science.

### **Overall Context**

One of the key requirements to enable the living laboratory approach is to build an institutional platform that allows multiple campus stakeholders to collaborate and share ideas. The University has made this possible through the creation of an Energy Action Team, organized within the campus Environmental Caucus.

The campus Environmental Caucus is composed of faculty, staff and students with an interest in environmental activities and sustainability decisions on campus. Within the Environmental Caucus is a subcommittee focused on energy issues, called the 'Energy Action Team.' This team works to identify and vet energy-related opportunities for the university to reduce costs, increase research, and meet environmental goals. The group includes research staff, directors of the utility services and sustainability offices, and faculty in engineering, business, and environmental sciences. A chief goal of this group is to enable faculty and students to engage in projects that are of immediate and direct service to the utility services or sustainability office, including data analysis, infrastructure assessment, programming, or broader informational needs, such as feasibility studies. The group's monthly meetings enable faculty and facilities staff to maintain and make progress on an ongoing list of on-campus applied research projects for students and faculty.

Because of this relationship between faculty and the groups tasked with monitoring and improving campus energy consumption, the faculty on the team were able to create several student projects in collaboration with the university's utility services department. Contexts for these projects included an engineering design course, a mechanical engineering graduate course, a computer science graduate course, an environmental science graduate course, and undergraduate research activity. All of these projects were mentored by faculty that were on the Energy Action Team. These projects are described below, along with the contexts in which they were implemented, and representative outputs generated by the students.

### **Undergraduate Engineering Design Course**

Within the engineering programs at our university, students receive 13 credit hours of design instruction. In their third year, the learning emphasis is on technical communication and the front-end stages of design related to problem clarification, concept generation and evaluation. Topics surrounding engineering economics and ethics are also woven through the course. To accommodate these learning emphases for a diversity of engineering disciplines (mechanical, civil, environmental and electrical engineering students), instructors theme the course to a specific problem that all students can address. The topic of campus sustainable energy solutions satisfied both the class structure and learning objectives.

At the beginning of a 15-week semester, the Director of Utility Services visited the class to discuss how energy is consumed and transformed on campus to meet electrical and heating demands. In this visit, data was shared that shows the changes in energy consumption throughout a day, a week, and over the year to demonstrate how the patterns of campus use and weather drives the energy demand. From this introduction, the students were assigned to teams of 4-5, and they were given a problem statement asking them to identify cost-effective technology

changes that would reduce the University’s greenhouse gas impact, scoped down to a particular campus operation (e.g. campus boiler plant or building).

Over the semester, the project was structured into smaller individual and team assignments that guided them along the design process. Initially, individuals were required to conduct state of the art literature reviews, assisted through University librarian lectures and classroom instruction on information literacy. As a team, students develop a problem statement with clearly defined engineering requirements. In a mid-semester design review presentation, the teams presented their understanding of the problem and their informed early design ideas to their client and the class. After this round of feedback, students embarked on more in-depth individual and team-based technical and engineering economic analyses (e.g. energy loads, energy costs, pay back periods, etc.) to evaluate the performance of their ideas based on their defined engineering requirements. By the end of the semester, the students wrote a design proposal to their client that recommended a series of solutions to adopt in order to reduce University emissions.

*Table 1. Subset of engineering criteria established by students working to redesign campus boiler operations.*

Objective	Description	Metric
Maximize boiler efficiency	The objective will focus on improving boiler efficiency, as it relates to the heat output [BTU] per quantity of natural gas consumed [therms].	$\frac{BTU \text{ heat output}}{Therms \text{ NG input}}$
Minimize water loss	Upon receiving a tour of the plant, it was discovered that there have been large quantities of water usage resulting solely from leaks within the system. Some leaks lasting longer than 3 weeks.	$\frac{gals \text{ H}_2\text{O saved}}{gals \text{ H}_2\text{O used originally}}$
Reduce CO <sub>2</sub> emissions	This objective will focus on reducing the greenhouse gases emitted from the boiler plant.	$\frac{mtons \text{ CO}_2 \text{ saved}}{mtons \text{ CO}_2 \text{ original}}$
Ease of maintenance	This objective will aim towards reducing the time and ease of maintenance for the technicians.	$\frac{time \text{ saved}}{original \text{ time taken}}$

In the first step of the design process, students gathered information from the existing systems on campus. Part of this work included scheduling meetings and interviewing plant and building technicians to better understand the existing systems, arranging plant/building tours and walkthroughs, and interpreting plant and building drawings to better understand the existing

systems before uncovering new strategies for their improvement. From this early information gathering, students were required to establish measurable engineering objectives and requirements, including those that were at odds with the major sustainability objectives of the project (e.g. reduce greenhouse gas emissions, reduce water consumption, reduce energy/demand costs). An example subset of student-defined criteria is shown in Table 1, which was for a project targeting a centralized boiler plant. The criteria were approved by their client - University Facilities - in a formal mid-semester design review presentation.

The mid-semester design reviews were communicated through a verbal presentation to their client (Director of Utility Services and relevant staff like the boiler plant manager) and class. In these reviews the students clarify the campus and client needs as engineering requirements and introduce their design ideas. The client has the opportunity to ask questions regarding their research, voice concerns about various ideas, and redirect or give a stamp of approval to the team before the students move along to the more detailed concept evaluation stage of their project.

For the natural gas boiler plant analysis, students identified a number of short-term design solutions to reduce greenhouse gas emissions and energy costs as well as more expensive long-term solutions. A short-term solution that was adopted by the University was tied to the operating schedule of the redundant boiler units. Students examined total plant thermal output data for the redundant boilers, and determined for a typical heating day only  $\frac{3}{4}$  of the main boiler capacity was in use. Figure 1 shows total boiler load generated from 2-3 boilers, in MMBTU, on a typical heating day. The data is shown alongside the outdoor air temperature to interpret the nature of the heating load. The major conclusion from this plot is that the max heating load on a typical heating day is only 75% of a primary boiler capacity. The major recommendation was to primarily run the single boiler, keeping all redundant boilers on standby for days with high heating loads (high heating degree days). The students learned that operating a boiler below its designed capacity causes the thermal efficiency of the unit to drop. By retaining high capacity of the primary boiler, it would sustain a higher efficiency and in turn generate more BTU in high temperature hot water for less natural gas. This operational change was estimated to save the plant \$20,000 in natural gas costs and 190 tons of CO<sub>2</sub> equivalent greenhouse gas emissions each year.

In another project focused on a campus sports arena, students once again evaluated a series of short- and long-term solutions to reduce energy costs and emissions. One of their major analyses was to consider the replacement of older belt-driven fans with more modern direct-drive fans within the HVAC systems. As part of their analysis, they conducted a detailed net present cash flow analysis for the lifetime of the device, and computed a simple payback period of 6.5 years. Similar analyses looked at the economics of replacing the current metal halide lighting system with LED technology.

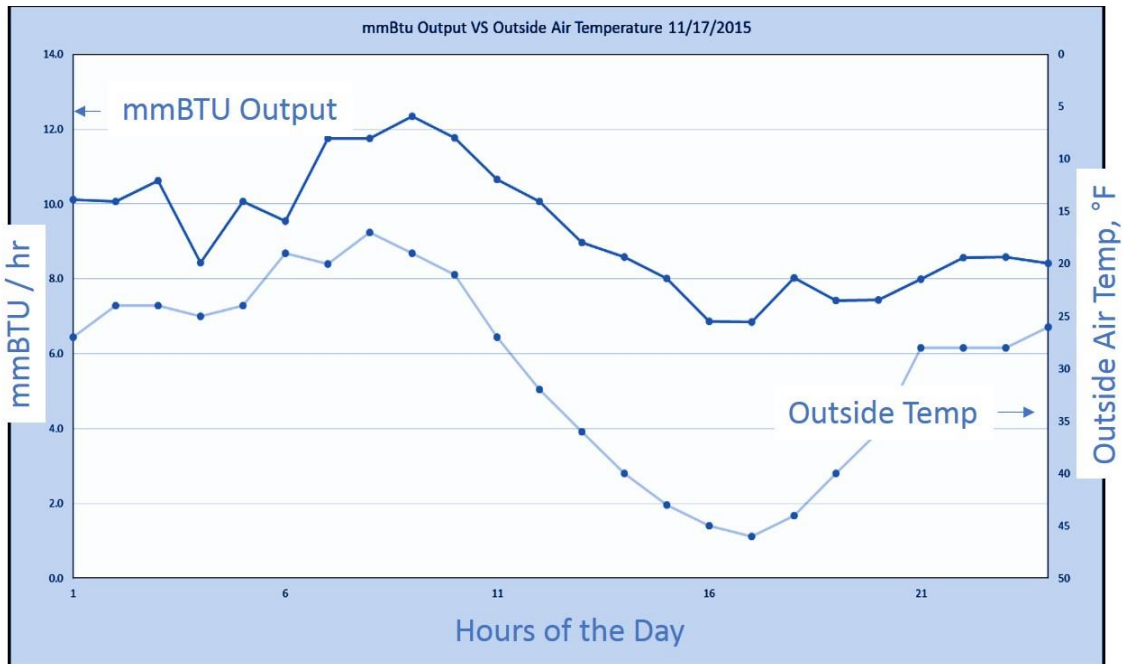


Figure 1. Data linking the thermal output of a central boiler plant in MMBTU/hr (dark blue line) to the outdoor air temperature in °F (light blue line) over the course of a 24 hour period.

### **Graduate Computer Science Course**

A graduate computer science course that was focused on informatics for smart and sustainable cities was developed and offered in Fall 2017. This course was project-focused, with students performing analysis on a variety of datasets for public institutions, including the city, county, and university. One of the data sources for these projects was the university utility data and operations data for the campus HVAC systems. As part of the course, students had to choose a dataset and identify a research question to answer from it. In collaboration with the campus utility services department, one student chose to do a project focused on developing algorithms to identify simple faults in the HVAC system from the operational data.

The graduate student who used campus HVAC operational data for his informatics project was able to develop a numerical code in MATLAB that could input operational data and identify the following faults:

- Cooling valves open during heating demand in an air-handling unit (AHU), indicating a control error or stuck valve
- Heating valves open during cooling demand in an AHU, indicating a control error or stuck valve
- Both heating and cooling valves simultaneously open, indicating a stuck valve
- Negative values in the data, indicating a faulty sensor

While a variety of commercial solutions exist for automated fault detection and diagnosis, these can be quite expensive, whereas the student’s code could easily be run and identify the most common fault types for a given HVAC component. Figure 2 below shows an example output from the code, identifying when each of the faults occurred for a given HVAC component, in this case an air handling unit.

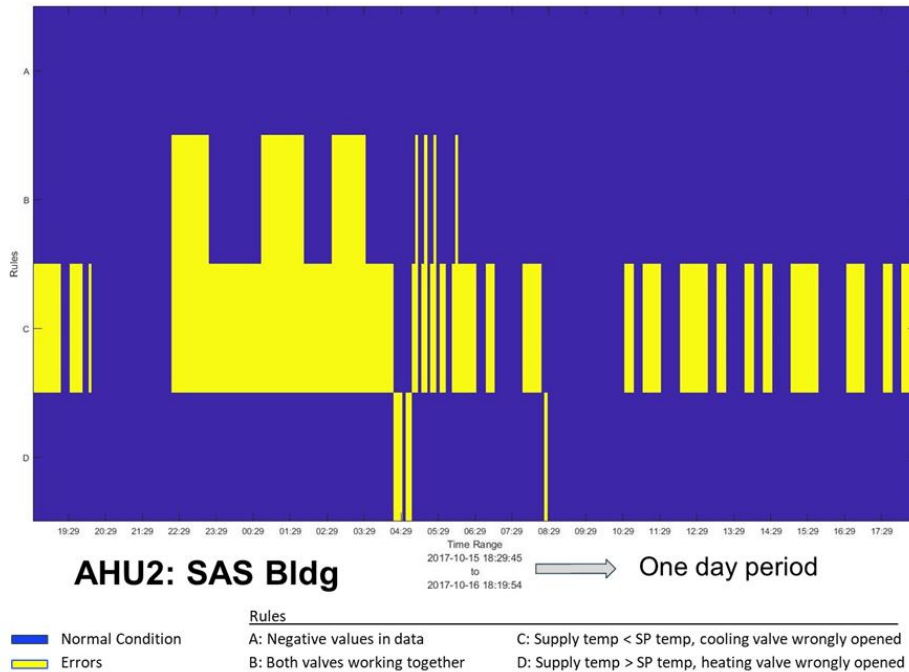


Figure 2. Representative fault detection output for a given HVAC component

## Graduate Environmental Sciences Course

The university has a Master’s program in climate science that includes a required course in energy technologies and policy. The class features a hands-on project to hone students’ applied analytical and public discourse skills. In Spring 2018, this course required students to obtain, synthesize, and analyze university building energy and water usage data, in order to provide recommendations for reduction in energy/water usage based on quantitative analysis. Student teams developed their own research questions using the data, identified analytical methods, performed the analysis, wrote white papers summarizing their research and recommendations, and gave presentations to utility services leadership and the university’s coordinating committee for campus sustainability.

In one project, the students performed a campus-wide characterization of building energy parameters by use type, attempting to build a multiple regression model to connect building-use type to energy loads. Another student project attempted to use energy consumption data from a historical campus building that was recently retrofitted with phase-change material (PCM) panels



to estimate the potential savings in other buildings with similar physical characteristics. PCMs can reduce thermal loads by absorbing and releasing large amounts of latent energy as they undergo a phase change from a solid to a liquid gel. These materials were contained and packaged into foil sheets, which were placed immediately above existing dropped ceiling tiles within the building. A third project made recommendations for broader implementation of individual LEED building-retrofit measures based on analysis of the before-and-after data from one campus building that had undergone the LEED process.

The students working on statistical regression had access only to total water, electricity, and heating usage data, and concluded that more detailed data including building use sub-categories were necessary to develop a statistically significant model for the energy consumption in the buildings. The students working on the PCM project had limited success applying their analyses of one building to another, in part due to challenges with the data. They normalized energy consumption by heating degree days (HDD) and plotted this metric over a period of time including pre- (2014-2016) and post-installation (2017-2018), which Figure 3 shows. The students attempted to use the BTU/HDD in the first building as a calibration to estimate the effect that installing the phase-change material might have on the second building, which was similar in vintage and usage to the first. The energy consumption in the first building dropped by 35 percent after the material was installed, and the building occupants reported greatly increased comfort in the workplace. The students' project estimated that the second building would reduce natural gas costs by more than 14 percent, resulting in about a seven-year simple payback period. However, the strength of the conclusions was limited because the students struggled with data anomalies and having insufficient continuous data to draw before-and-after conclusions.

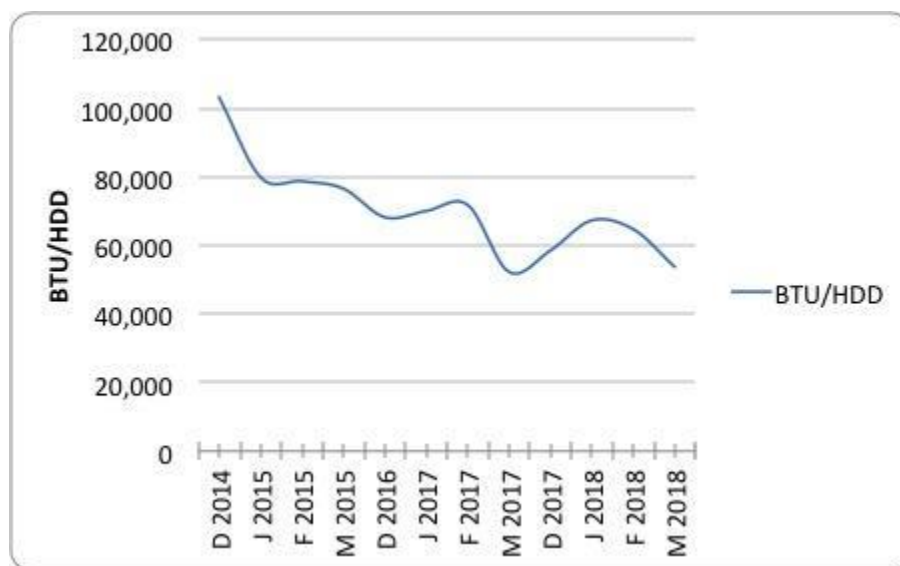
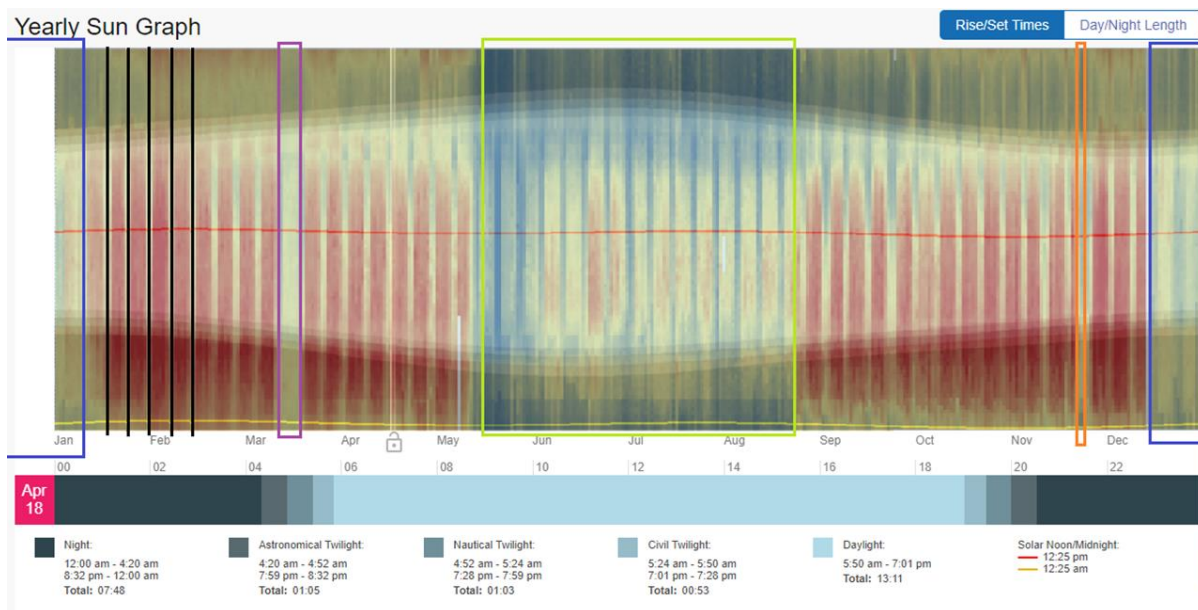


Figure 3. Example student-generated plot of historical energy consumption per heating degree day with installation of phase change materials (starting in 2017). Note that the students plotted the data only for December to March of each year.

## Graduate Mechanical Engineering Course

A graduate mechanical engineering course on energy systems analysis that covered the electricity, buildings, and transportation sectors was developed and offered in Spring 2018. This course was project-focused, and the project for the buildings unit of the class focused on analyzing energy data from buildings on campus to i) understand the causes of campus electricity demand peaks, and ii) identify appropriate solutions to reduce the peaks. The northern and southern ends of campus were on separate electric meters, with the northern end exhibiting a single daily peak and the southern end exhibiting two daily peaks. Additionally, energy data was available for most individual buildings on north campus but not south campus. Finally, one building on campus had detailed sub-metered data available for a variety of end-uses. Students formed teams and were tasked with combining these various data sources and building use types to gain insight into the causes of the peaks on south campus and recommend appropriate energy efficiency measures to reduce those demand peaks.



*Figure 4. South campus electricity heat map overlaid with sun graph, showing correlation between second evening peak and sunset. Each vertical line of data represents the energy consumption over a 24-hour period, and there is one vertical line for each day of the year along the x-axis. Red indicates high energy consumption, while blue indicates low energy consumption. The brightness of the sun graph indicates daylight hours. Also identified in the graph are winter break in blue, weekends in black, spring break in magenta, summer break in green, and thanksgiving break in orange.*

After investigating and synthesizing the various data sets, each of the student teams worked to identify the causes of the electricity demand peaks on south campus. Each of the teams chose their own approach and some demonstrated a lack of clarity regarding the nature of the project.

Some students focused on energy efficiency measures to reduce energy consumption, not recognizing that the project was focused on understanding the causes and reducing the size of the electricity demand peak. The team that did the best job of focusing on the peak plotted a heatmap of the electricity consumption for each day of the year on south campus, and then overlaid it with a graph of daily sunlight, which Figure 4 shows. This graph showed a strong correlation between sunset time and the second (larger) electricity consumption peak on south campus, indicating that the peak is driven by lighting demand. Correspondingly, they recommended energy efficiency measures focused on lighting, as well as thermostat adjustments to reduce HVAC demand.

### **Undergraduate Research Activities**

There were a number of monitoring activities that the campus utility services wanted to be able to do, but lacked the time because of resource limitations. A team of three undergraduate students was recruited during the Spring 2018 semester to identify faults and other operational errors within the campus HVAC systems. These students were given access to the campus HVAC monitoring and control software (in 'read-only' mode) and tasked with reviewing operational data for heating and cooling systems as well as building setpoints. The students spent the first few weeks of the semester learning about the campus HVAC systems and their variation between buildings, as well as learning how to use and access the data in the control software. The student team members were each assigned a subset of the buildings on campus and then had weekly research meetings in which they would provide updates on what they found in the data, with an emphasis on identifying HVAC systems or building setpoints that were functioning abnormally.

The students were able to identify a number of operational problems with the campus HVAC systems. In some cases, their identification of an issue led to an immediate action, such as identifying a cooling valve that appeared to be stuck open in a building, causing the heating system in the AHU to be working non-stop for several weeks to fight against the cooling. In other cases, they noticed when variable air volume (VAV) boxes were oscillating rapidly between heating and cooling, indicating faulty sensors, actuators, or both. They also noticed that several buildings appeared to not be following their defined occupancy schedules, in which setpoints should roll back in the evenings when the buildings were unoccupied, an example of which is shown in Figure 5. All of these operational issues provided opportunities for significant energy savings and were easily identified by undergraduate students with no previous training, providing a valuable source for additional labor and time while also providing the students with a valuable real-world learning experience. The university saved at least \$40k by not having to hire a contractor while getting similar quality of output, and the students' work was used to justify and secure additional funding for ongoing monitoring activities by Facility Services.

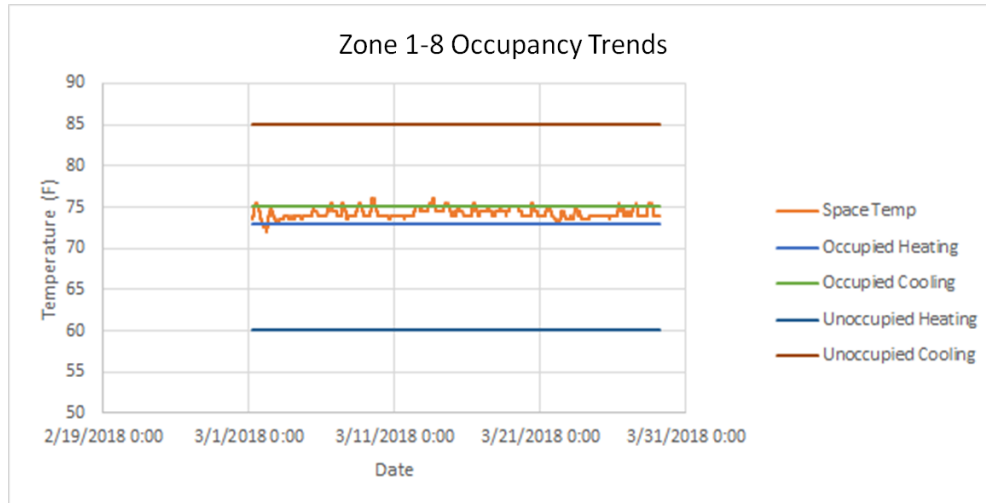


Figure 5. Space temperature over a 1-month period showing the building zone maintains occupied setpoint conditions full-time instead of rolling back to unoccupied setpoints during the night.

## **Discussion**

The suite of implemented projects achieved mixed results, varying both in their educational effectiveness as well as their effectiveness in achieving beneficial energy outcomes for the university.

The integration of real-world campus decisions and current data allowed the students to experience the challenges of data manipulation, visualization and analysis, experimental design, and the development of research questions in a meaningful and personally relevant manner that could not be achieved through a theoretical project. In the classroom and the textbook, devices always work and controls always perform as they are supposed to. In contrast, the students involved in these projects had to learn how to manage data streams with errors and gaps and physical systems that malfunction and do not work as intended. While these presented challenges for students, they gave them exposure to the difficulties of working with real-world systems and resources and the need for making estimations and assumptions.

In the undergraduate engineering design course, many students commented on the challenges of understanding and interpreting operational data that was critical to understanding their base design. In several instances, data was encountered that did not make sense, many times because the measurement devices were operating incorrectly. Managing this through early team/faculty or team/client meetings worked best to keep the projects on track. These instances provided opportunities to identify what was known and what was not known, and when it was appropriate to make approximations or assumptions.

Students in the climate sciences program tend to have a particular desire to solve local problems and address challenges that they experience personally. Participation in an important, local decision process through data analysis also reduced students' apprehension about learning to use technical and analytical methods and tools, because they understood the context of the process and had a vested interest in the project outcomes.

Both the engineering and climate science students found the project experiences to be valuable in their professional training. Many engineering students went on to use the examples of their design proposals as talking points on resumes, cover letters and eventually job interviews to illustrate how they were able to take real-world problems and challenges and find a working solution. For the climate science students, their participation in large-institution decision processes strengthens their professional qualifications, as affirmed by the program's industry advisory board and suite of organizational and industry partners.

A major lesson learned through these courses is that feasible project outcomes cannot always be achieved in a semester-long course or independent study. One approach to manage this is to re-introduce the same projects in subsequent semesters or years, allowing a new cohort of students to learn from and improve upon the work of their fellow classmates in prior semesters, while the faculty and staff administering the projects continue to gain deeper knowledge of the projects and relevant systems and data. The notion of building upon others' work emphasizes the need for continual project improvement. It also provides the opportunity of acknowledging the efforts of prior work, and understanding where new work and interpretation begins. This process of project re-introduction could be facilitated by introducing a campus-wide website that showcases the examples of how energy data was used in the classroom to foster new ideas amongst student, faculty and staff, similar to the approach taken by Duke's Campus as a Lab [7]. Such a system will also motivate the monitoring or verification of implemented student projects, enabling new streams of studies, such as investigating possible rebound effects due to energy efficient upgrades or building control settings.

Another challenge that the students encountered was in data availability. On a campus with a larger number of buildings, the practical challenges of logging enough data on energy consumption to separate the effects of climate, usage patterns, and relevant energy subsystems can be significant. Frequently, data was not available with enough subsystem or building granularity, or with enough history to understand patterns. The large amounts of data required to monitor each subsystem for an extended amount of time becomes infeasible. Strategic planning is necessary to determine the data needed and the relevant intervals and time periods over which it is needed. Understanding electricity peaks may require 5-minute interval data, while daily energy consumption data may be sufficient for analysis related to thermal loads. Purchasing portable electric meters with data logging capability allows more flexibility to gather additional needed data for a variety of loads. A current project with computer science students is focused on

building a dashboard to make data easier to view and access, which was born out of the data-related challenges of previous projects.

Challenges were also encountered in the utilization of the results of the students' work. Student reports could make recommendations, but without the resources to implement the recommendations, no change would result. Similarly, while the informatics student was able to build a software tool, resources are needed for someone to run the software and input the data. While the undergraduate researchers could identify operational issues with the HVAC systems, new problems will always arise and still require labor to continue the monitoring activities.

While the implemented projects achieved a variety of beneficial educational outcomes for students, the collaboration between the academic staff and facilities staff is what enabled beneficial outcomes to the university. The benefit to the university could have been even larger with increased institutional support. Release time is needed for facilities staff to be able to work with students and provide project oversight. While the projects could be integrated within existing faculty teaching loads, faculty that oversee such projects need to receive credit and value for their efforts, which can be difficult both for tenure-track faculty who are evaluated based on research publications as well as non-tenure-track faculty with high teaching loads.

In reflection of these lessons learned, we plan to continue to implement these projects in classes wherever relevant, including both design- and energy-focused courses, in addition to independent study and research projects. Continuous project refinement is needed to ensure that projects are well-defined and tractable for students. All projects will require regular feedback and interaction with facilities staff to ensure both project relevance and implementation of project results. Finally, the continued pursuit of institutional-level resources will be needed to provide the time, rewards, and investment to further this program that is beneficial to both students and the campus as a whole.

## **Conclusions**

This paper describes the development of several student projects that utilized real system data for campus energy operations at our university. Students gained experience working with the messy data and malfunctioning components of real systems while also seeing how their classroom content related to the devices operating around them. The success of this method relied on the availability of data along with frequent communication between faculty, students and the facilities department. Through this initial implementation, we have laid a foundation of relationships, data access, and projects for an ongoing pipeline of collaborative projects between the academic and facilities sides of the university that will serve both educational and environmental interests going forward.

## **References**

- [1] P. Ballon and D. Schuurman, "Living labs: concepts, tools and cases," *Digital Policy, Regulation and Governance*, vol. 17, no. 4, 2015.
- [2] C. Veekman, D. Schuurman, S. Leminen and M. Westurlund, "Linking Living Lab Characteristics and Their Outcomes: Towards a Conceptual Framework," *Technology Innovation Management Review*, vol. 3, no. 12, pp. 6-15, 2013.
- [3] T. Cohen and B. Lovell, "The Campus as a Living Laboratory: Using the Built Environment to Revitalize College Education," Sustainability Education & Economic Development Center by The American Association of Community Colleges, Washington DC, 2018.
- [4] T. Lindstrom and C. Middlecamp, "Campus as a Living Laboratory for Sustainability: The Chemistry Connection," *Journal of chemical Education*, vol. 94, no. 8, pp. 1036-1042, 2017.
- [5] T. Lindstrom and C. Middlecame, "Campus as a Living Laboratory for Sustainability: The Physics Connection," *The Physics Teacher*, vol. 56, no. 240, pp. 240-243, 2018.
- [6] J. Evans, R. Jones, A. Karvonen, L. Millard and J. Wendler, "Living labs and co-production: university campuses as platforms for sustainable science," *Current Opinion in Environmental Sustainability*, vol. 16, pp. 1-6, 2015.
- [7] Duke Office of Sustainability, "Campus as Lab," [Online]. Available: <https://sustainability.duke.edu/academics/campus-lab>. [Accessed 30 January 2019].