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Visualizing building energy demand for building peak energy analysis

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ABSTRACT

To better identify how to reduce peak demand charges for a university campus, we investigated the relationship between individual building peak demand and the campus peak energy use by evaluating the pattern of energy use across time and day. To facilitate this evaluation, we developed a pivot table analysis tool that enables ready cross-building comparisons in a visually intuitive display. We used a university campus as an example to facilitate potential peak demand charge savings based on analysis of which buildings contribute to peak energy demand, and understanding the factors contributing to that building-dependent energy demand.

1. Introduction

The U.S. electric utility industry widely adopted a demand-charge rate structure starting around 1905 to 1915 to charge consumers based on the maximum power consumption within the billing period, in addition to charging for the total amount of electricity consumed during that billing period [1]. For large commercial and industrial users, the electricity demand charge is usually separated from the total consumption charge in their billings, and is charged at a significantly higher rate. Within a multi-building complex, like a university campus, controlling energy costs depends on understanding which buildings contribute to peak energy demand, and understanding the factors contributing to that building-dependent energy demand.

Peak demand for a given building is comprised of two factors: quantity and timing. There are four ways a building can interact with the campus peak:

- High demand with little daily fluctuation.
- Low demand with little daily fluctuation.
- Daily fluctuations that coincide with campus-wide pattern.
- Daily fluctuation that is opposite of the campus-wide pattern.

The first is large magnitude demand, regardless of timing. If a building has a high demand all the time, it is more important to peak demand than a building with low daily demand. The second factor is coincidence of demand. Many buildings exhibit daily peaks and troughs of energy use. If the peak for a single building occurs around the same time as the multi-building campus's peak, that building is contributing to the campus peak. A building with a large magnitude demand that peaks at the same time as the multi-building campus is a very good candidate to investigate if the goal is to lower monthly peak costs for the whole campus. Conversely, a building that peaks at night is not going to yield the same savings return.

Buildings with energy usage of large magnitude contribute to the campus-wide billing peak regardless of the timing of their particular building peak. These buildings contribute to the base load portion of a billing-peak (often every billing period). Buildings with peak-demand that coincides with campus peak contribute directly to the peak-demand portion of the campus-wide billing-peak, however small in magnitude their individual contribution may be. Buildings that meet all of the mentioned conditions that allow them to contribute coincidentally timed, large magnitude peak-demand have the greatest potential to "drive" the campus-wide billing-peak.

Seasonality complicates campus-wide analysis of which buildings drive peak demand. Some buildings are intense and consistent electricity users year round, but the majority vary according to the season. On a university campus, some of this seasonal variation is driven by the seasonal nature of student populations. A large portion seems to be driven by the particulars of a building's heating, ventilation, and air conditioning (HVAC) systems.

2. Available energy visualization tools

We reviewed energy visualization tools available through the Internet or presented in the literature. Most of the energy visualization tools apply simple lines, columns and bar charts to display

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the electricity usage patterns over time for each individual building. The major goal of these tools is to provide comparable energy usage data over time and under different weather conditions for each building. For example, The Pulse Dashboard (Pulse Energy, Vancouver, British Columbia) [2] and iBEnergy Software suite (Quality Attributes, Ames, Iowa) provide 2-D trend line energy consumption data for each commercial building. Building Dashboard (Lucid, Oakland, California) [4] and Energy Efficient Education Dashboard (Quality Automation Graphics, Ankeny, Iowa) [5] provide energy usage using 2-D columns. Other visualization tools target understanding energy consumption of different buildings in the same region. For example, Howard et al. [6] built a visualization model presenting the building estimated annual energy (kW h/m^2 floor area) at the block level and at the tax lot level in New York City.

Very few building visualization tools have the advantage of investigating the building peak demand patterns, or are designed to investigate the peak patterns of buildings. Jenkins et al. [7] used a standardized energy demand visualization tool to examine the monthly profiles for substation and synthesized equivalent, which is similar to the data visualization tool used by Meyers and Chen [8]. Meyers and Chen graphed a contour plot showing energy intensity with various operating stages of occupancy sensors, which clearly indicated the status of lights in the building and assisted building managers in determining the disadvantages of using occupancy sensors as light switches.

Another way to visualize building energy demand is to project the energy use into the third dimension (z axis), as shown in the figure below. Fig. 1 shows daily building energy demand in a month. One can observe from this graph a sharp increase in energy demand at day 16 and the peak demand at day 28. However, this visualization tool is only useful for investigating energy demand in one building and is not as useful for comparing energy patterns of several buildings, especially over the course of a full year.

3. Methodology

In order to better visualize building energy use over the course of both time of day and days of the year, and in order to better visualize peak energy demand periods, we developed a new visualization tool that is capable of translating the real time, every 15 min data generated by the building energy meters into a coloured graph (an energy use heat map over time and day). These energy “heat maps,” normalized by building, enable ready visual comparison of patterns of energy use across buildings and compared to the main campus energy meter.

Using this new visualization tool, we examined the relationship between campus demand and the individual building peak demand. In order to understand which individual buildings are contributing to the campus peak and to facilitate energy savings based on the analysis, it is critical to investigate both the timing and magnitude of individual building energy peak demand. We provide an example of how this new visualization tool can be used to evaluate the relative contribution of different buildings to total campus peak energy demand.

3.1. Visualizing energy demand timing

In order to visualize demand across time, a heat map system was developed using a spreadsheet (Excel, Microsoft Corp, Redmond, WA). The heat map is used to visualize average demand for a given time, day of the week, and time of the year (in this case, averaged by quarter). The maps summarize the hourly data pulled from the real-time, building-specific, monitoring ION 7550-8000 series meter (Schneider-Electric, France).

The ION meters report every 15 min to the campus electronic metering system (EMS). Our campus has roughly 160 ION meters, mainly monitoring new buildings, science buildings, and other large energy demand buildings. By organizing those meters into a tree structure, the EMS can calculate demand and usage information even for buildings not directly metered. In these cases, buildings not directly metered are assigned a “virtual meter” and their usage and demand data is stored alongside data from actual meters. Data points are collected for each meter and calculated for each virtual meter every 15 min. The calculations that produce each building's virtual meter have been validated through a careful quality control process for many, but not all of the buildings on campus.

3.2. Pivot table setup and formatting

The raw data being input into the pivot table had the following fields of data: a date/time stamp, a building name, usage or demand data point, and several calculated fields for aggregation purposes (day of week, hour of day, quarter, month, year, etc.). Upon inserting the raw data in a pivot table, we inserted average energy demand as our value, quarter and hour as our column fields, and building name and day of week as our Row fields. Each building's field of values was conditionally formatted with the color ramp of red to green being highest to lowest (demand). Row and column sizes were set approximately equal to each other for a square grid look (110 pixels). Building names and day of week labels were set to size 100 and 72 fonts, respectively, and large labels were added above the pivot table for the quarters. The top header rows of the pivot table were hidden.

4. Results and discussion

As shown in Fig. 2, below, each cell of the figure shows hours of the day across the columns from 0:00 to 23:00. The seven rows are days of the week, Monday through Sunday. Each building meter is normalized to its own year of data. The coloration of the cells ranges from red representing the highest averaged energy demand for that building to green representing the lowest demand values for that building. As seen in the third panel, the year of data has been grouped into quarters of the year.

The meter listed below is the main meter for the majority of the campus. This meter can be seen to draw its highest demand through the second and third quarters, but has a distinctive weekly and hourly pattern (highest during the day on the five weekdays) year round.

4.1. Campus summary

The electricity use on campus as a whole clearly peaks in the warmer months. In the summer, the chiller plants and the distributed air-cooling across campus run exclusively on electricity. In cooler months, most of the building heat used on campus originates from the steam plant, which generates steam using natural gas.

4.2. Analogous loads

Many buildings behave much as the entire campus does. The chillers behave most similarly to the campus meter. This is also true for networking and computer facility buildings, which have their own chillers (not included in the figures). The science buildings in Fig. 3 (Science 3, Science 2, and Science 1), behave similarly to the master campus meter, but have more pronounced daily peaks. In comparing Science 2 to Science 3 and Science 1, a few differences stand out. Science 2 has more extended peak demand periods and

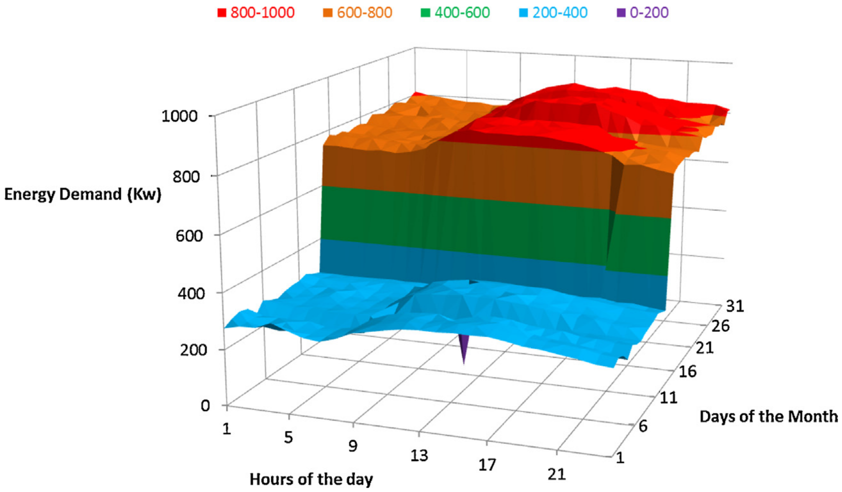

Fig. 1. *Energy demand of one building.* Energy demand of Science 2 building for January 2013 illustrating the low energy demand during the winter holidays and the rapid increase in energy demand once school began again. The pattern of energy consumption by building in Science 2 is similar to the pattern of energy consumption for the campus as a whole, as quantified by the main campus energy meter. Peak energy occurs daily starting about mid-morning. In most classroom and administration buildings peak energy (red) decreases dramatically starting about 5:00 p.m., while Science 2 (as is true for many of the science buildings) continues peak energy use through the early evening. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

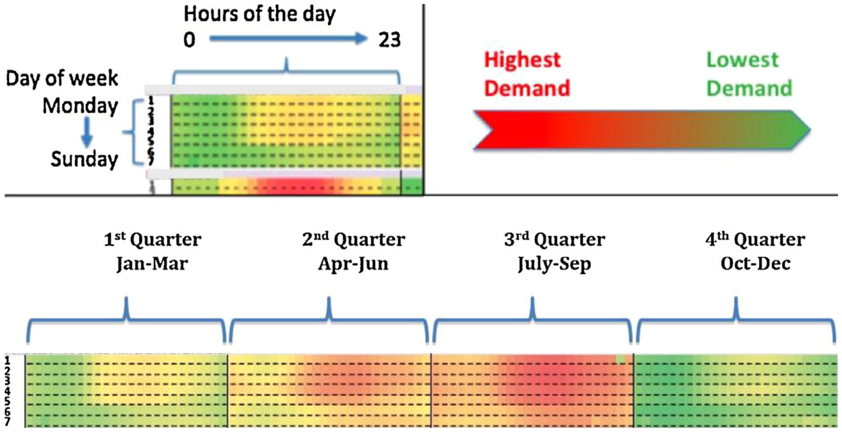

Fig. 2. *Heat map visualization of campus demand—how to read the heat maps.* Illustration of how to read the heat maps. Columns represent hours of the day, from midnight to 11 p.m. Rows represent the days of the week, with the weekends at the bottom. Each quadrant in a series of heat maps represents the year in three month segments. Each data point is the average of all the days in that period, averaged by hour of the day and day of the week.

the same pattern of decreased demand in the fourth quarter, but at a drastically reduced level. Interestingly, Science 1 and Science 3 do not seem to be affected by the seasons at all. This energy demand pattern could be demonstrating that the equipment used in these buildings is much more energy intensive than the HVAC system.

Beyond chillers and science buildings, academic buildings show similar daily peaks (Fig. 3). Some buildings, such as Academic 3 and Academic 2, show more intense energy demand in colder weather (Quarter1 and 4), while Academic 4 shows more intense energy demand in warmer weather (Quarter 4 data not available due to building renovations). These patterns, while in some ways similar to the science buildings, are interesting since the buildings are used completely differently. A detailed comparison of the building envelopes, HVAC system components, or other factors might help highlight the differences and commonalities. Academic peaks are probably more due to high building traffic (especially students) than room equipment use.

4.3. *Off-peak loads*

A few buildings, primarily dormitories, peak off hours (Fig. 4). During the day the students are in their classes or studying, therefore the demand at their dwellings is lower. The evening is the most energy intensive portion of the day, after everyone has returned home and is moving around, using TVs, computers, and charging phones (Dorm 5 A). The parking garages use little electricity besides some large lighting fixtures, which only need to come on at night. Dorm 5 A and C exhibit another interesting pattern in that the residential towers follow the dormitory pattern, while Dorm 5C, comprised of the common area and a café, follows a very different pattern concentrated in the fourth quarter. Dorm 3 is an interesting case since it serves an administrative and residential role simultaneously. The residential pattern is very clearly drowned out by a chiller type pattern, which almost mirrors the campus meter pattern.

4.4. *Quantifying the visuals*

“Heat maps” facilitate a visual comparison of the timing of energy demand; but to quantify the phenomenon examined in the visual analysis, the “Coincidence Factor” concept was used, borrowed from utility-scale peak analysis. The concept is defined as follows:

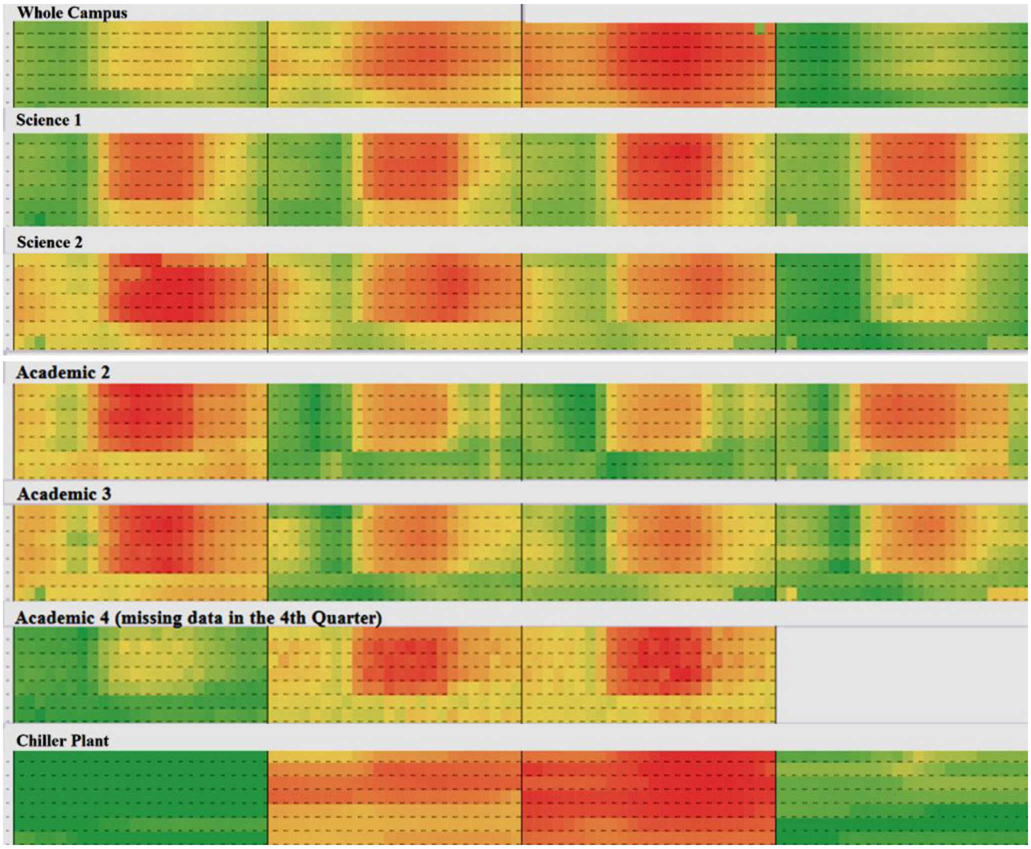

Fig. 3. *Visualizing loads analogous to campus whole.* These maps illustrate the patterns of energy consumption for the two types of buildings that, as a group (and other than the data center), represent the highest energy demands on campus: chiller plants and science buildings. The top heat map shows the pattern of the energy used for the whole campus for a single year (October 2012 through September 2013), with the quadrants rearranged to represent a full year from January through December. Chillers clearly show the same seasonal pattern. The science buildings show the same daily patterns of energy use. Notice that some science buildings (example Science 1) tend to decrease energy consumption earlier in the day than others (Science 2). These heat maps illustrate that the academic buildings follow the similar daily pattern of energy consumption as does the whole campus, but illustrate that most academic buildings are underutilized during the summer. Note that in the summers, classes tend to be held only during the day, while during the fall and spring terms classes are held across campus into the evenings, as evidenced by the extended energy use into the evening.

> "**Coincidence factor** is the fraction of the peak demand of a population that is in operation at the time of system peak. Thus, it is the ratio of the population's demand at the time of the system peak to its non-coincident peak demand. The peak demand use for a given building and end use are typically not aligned exactly with the utility system peak, which is how the avoided peak demand is defined. For example, if at the time of system peak, only 3 of the 7 CFLs [Compact Fluorescent Lamps] mentioned above are on, then the coincidence factor is 3/7."[9]

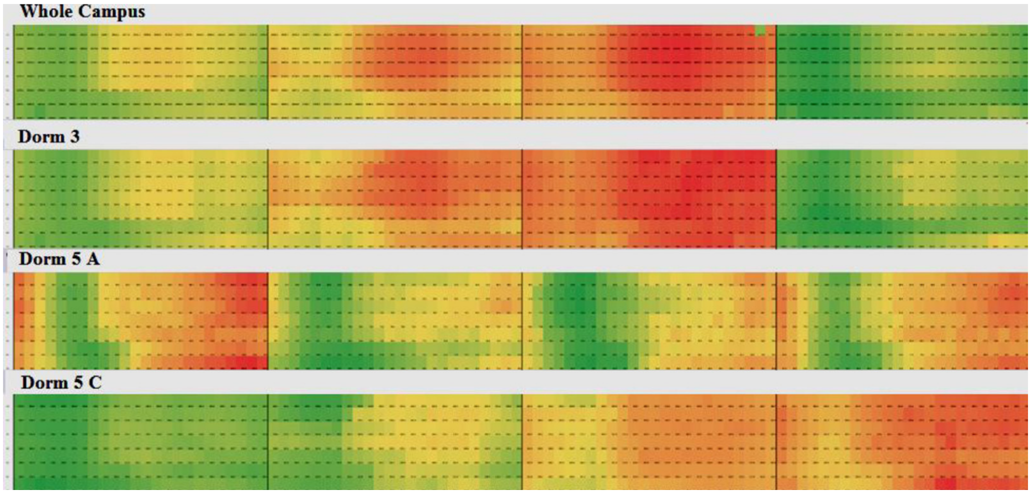

Fig. 4. *Visualizing off-peak loads.* Unlike the academic, administrative and research buildings, the dormitories illustrate an energy consumption pattern very different from the campus as a whole, as students tend to be away from their dormitory rooms while they are in class. Dorm 3 is a mixed use building with both offices and dormitory space, which is illustrated by the pattern of energy use that mirrors the whole campus energy use patterns.

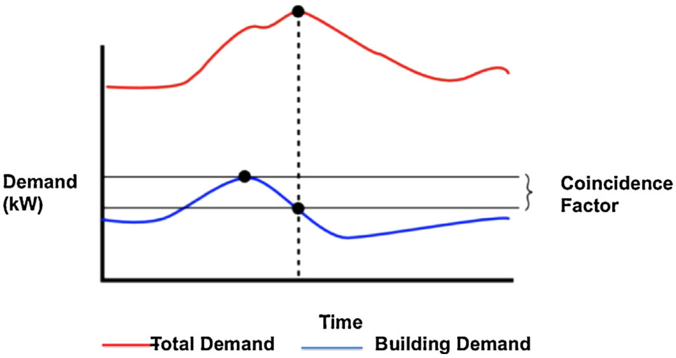

Fig. 5. *Coincidence factor (modified from Stern, 2013 using made up data).* Illustration of the calculation of coincidence factor for each building using the total campus demand and the individual building demand data.

Fig. 5 illustrates the coincidence factor concept. Coincidence factor measures the ratio of a building's demand at the time of the campus peak, relative to that building's own peak. This process is analogous to normalizing building demand to itself, per building, as was done in the heat map visualizations.

Using coincidence factor to analyze any building's proportional contribution to campus-wide peak facilitates the identification of buildings that contribute a greater portion of their own demand to campus peak demand at the moment of the billing peak. This information is summarized for the top 10 coincidence factors on campus in Table 1.

Table 1
Top 10 coincidental demands by building, campus wide.

Rank	Building name	Average coincidence factor (%)
1	Science 2	92.6
2	Science 1	91.5
3	Science 3	90.7
4	Academic 6	89.7
5	Academic 7	87.6
6	Academic 3	86.7
7	Academic 2	79
8	Academic 8	77.2
9	Multi media 1	76.5
10	Office 1	75.2

Large science buildings immediately emerge as top contributors to campus peak timing. With average coincidence factors of approximately 90%, science buildings are drawing nearly all of their individual peak loads at the same time that the campus-billing peak occurs. Academic buildings occupy a second rung with average coincidence factors in the high 70 percent to high 80 percent. Dormitories occupy a third rung; however, no dormitory makes the top 10 list. In general, buildings where people use special equipment to perform activities, and buildings with expansive machine rooms appear to be highly placed on the list.

Academic 7 and Academic 6 buildings have the highest coincidence factors of the non-laboratory academic buildings and so their peak demand period overlaps the most with the campus peak demand of all the academic buildings. This analysis, like the heat maps, considers only demand timing and so a high coincidence factor could have variable implications. A high coincidence factor alone does not mean that the building will contribute greatly to campus peak. If a building has a lower than average peak demand magnitude, then it will contribute less to the campus peak. Alternatively, if a building is responding to similar external temperature and occupancy conditions as other buildings and that response is proportionately higher than the similar buildings, and the coincidence factor is high, then this example building would present a targeted opportunity for peak shaving.

Fig. 6 presents a visual comparison (using the heat map tool) between a building's time aspects of demand for several examples of building types (science, academic classroom, dormitory, parking garage) listed by the average coincidence factor associated with that building. Analogous loads have higher values of coincidence factor and off-peak loads have lower values. Chiller plants are conspicuously absent (have a low overall coincidence factor) because their extremely high coincidence factors in the summer are attenuated by their rather low coincidence factors in the winter. While the heat maps are effective tools for visualizing the timing aspect of building demand and coincidence factor is an effective tool to quantify that aspect, both tools remove the magnitude component of a building's demand. However, magnitude is also important. For example, a small heated shed with a single light whose demand is coincident with peak stands out in this timing analysis relative to a large-magnitude constant-demand building but is inconsequential as a contributor to campus peak.

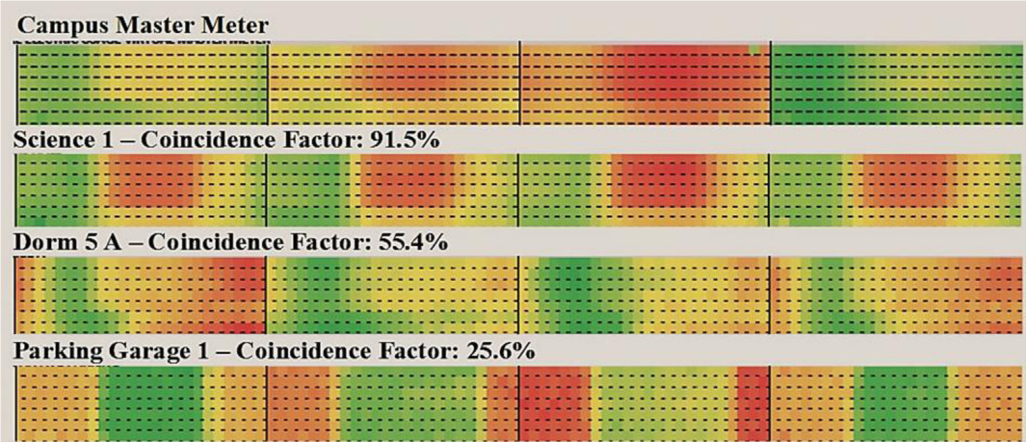

Fig. 6. *Comparing coincidence factor to heat maps:* Heat maps of buildings with different coincidence factors, from highly coincident with campus peak energy use (92.6% coincident) to poorly coincident with campus peak energy use (25.6% coincident), illustrating the very different patterns of energy use in different types of buildings across campus, and illustrating the potential for using coincidence factor as a representative of contribution to campus energy demand for energy modeling.

5. Conclusion

With real-time metering data available, and energy visualization tools, electricity users and managers can investigate the timing of building demand peak and help identify target buildings for savings on the peak demand charge. Using this new visualization tool, especially in combination with the coincidence factor, energy managers can begin to better understand the relationship between their billing peak and individual building peak energy demand. Clear identification of the timing patterns of energy demand enables an assessment of what activities and building uses are contributing to those peak energy demands, which is the start of building energy management. Looking at the energy demand pattern alone is not enough. The overall magnitude of the energy demand is also, obviously, important and needs to be considered in the analysis. In short, this new heat map visualization is an easy tool to use to help identify the buildings within a multi-building complex that contribute disproportionately to peak energy demand.

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