FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 29, N^{o} 3, September 2016, pp. 325 - 338
DOI: 10.2298/FUEE1603325C

DESIGN AND TECHNOLOGIES FOR IMPLEMENTING A SMART EDUCATIONAL BUILDING: CASE STUDY

Ionut Cardei, Borko Furht, Luis Bradley

Department of Computer & Electrical Engineering and Computer Science
Florida Atlantic University, Boca Raton, Florida, USA

Abstract. *In this paper we describe the design of an educational smart building and the innovative technologies that were implemented. In January of 2011, Florida Atlantic University opened its new LEED Platinum-Certified "Engineering East" building. The building was designed as both a model of how new technologies can drastically decrease the energy requirements of a large university building and for providing a "living laboratory" so that students and faculty may actually see how these systems work and interrelate. Engineering faculty was involved in providing inputs to the builder in creating state-of-the-art engineering laboratories.*

Key words: *smart building, living laboratory, sensors, LED-certified, power analysis*

1. INTRODUCTION

The development of smart buildings has gained the importance, so innovative techniques can be created to optimize the operation of the building in order to reduce expenses and save energy. Recent research deals with various approaches and related technologies in designing smart buildings [1-6]. In designing our educational smart building and providing research ability, the building is outfitted with hundreds of different sensors that record everything from the temperature of the cold water entering and leaving the building to the amount of electricity generated by the solar panels on the roof and walkways to level of CO2 in a lab at a certain time. The paper provides an overview of the various innovative systems implemented in our new "Smart, Green Building," shown in Figure 1, and highlights the various sensors and data available for analyzing these systems, both in real time, and through storing this data and processing it through data mining routines. Several research projects as part of the "living laboratory" are described.

Received June 25, 2015

Corresponding author: Borko Furht
Department of Computer & Electrical Engineering and Computer Science, Florida Atlantic University, Boca Raton, Florida, USA
(e-mail: bfurht@fau.edu)

1.1. What is LEED

The LEED or Leadership in Energy and Environmental Design green building certification program is a voluntary, consensus-based rating system for buildings designed, constructed and operated for improved environmental and human health performance. LEED addresses all building types and emphasizes state-of-the-art strategies in five areas:

1. Sustainable and development
2. Water savings
3. Energy efficiency
4. Materials and resources selection, and
5. Indoor environmental quality.

Points are attempted in each of these five areas in order to achieve a silver, gold, or platinum level of certification based on the type of project. When the building was completed in 2011, a minimum of 52 points were required to achieve platinum level certification. Engineering East achieved 55 points. The LEED Scorecard for the building is given at: http://www.eng.fau.edu/pdf/green_bldg_scorecard071411.pdf.

Fig. 1 LEED Platinum-certified engineering building at FAU

2. MAIN BUILDING SUBSYSTEMS AND THEIR DESIGN

Innovative technologies were implemented in the following subsystems:

- HVAC System (Heating, Ventilation & Air Conditioning),
- Cloud Computing System and its Network Control
- Power generation system and its control.

The mechanical equipment and sensors, installed on the 1st floor, are shown in Figure 2.

Fig. 2 Mechanical equipment, pumps, piping, and sensors

The building is equipped with hundreds of sensors that measure and collect various parameters and display them in real-time on the dashboard, which is accessible through a Web-based application called DeviseWise, created by ILS Technology. The DeviceWise system periodically captures sensor data from the building's electrical, computing, and air conditioning systems and stores the information in a database. The system then provides a Web-based application that displays the summarized information in an energy dashboard accessible from any Internet browser. DeviceWise also provides an API that allows other programs to access the data stored in the database for extraction and reporting outside of the energy dashboard. Figure 3 shows the dashboard indicator with a menu of views. The selected view is 1st floor temperature.

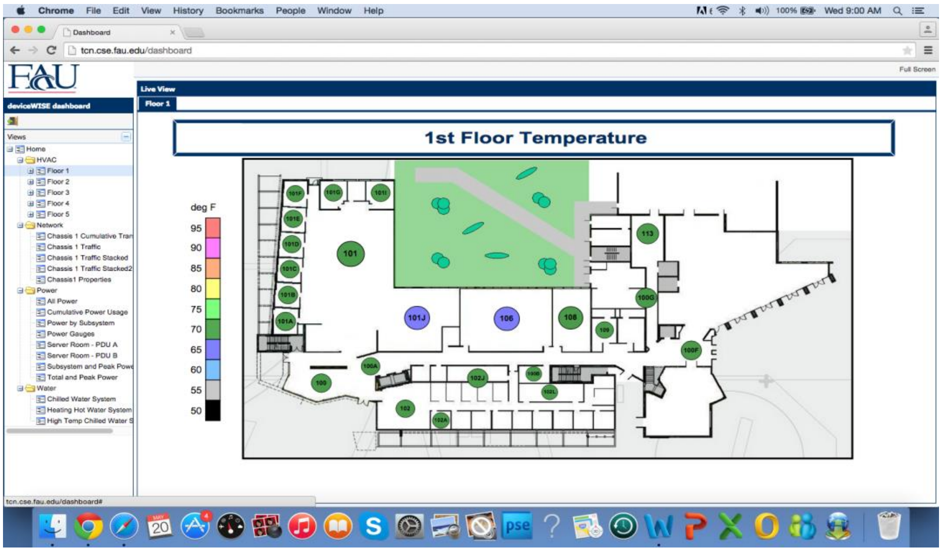


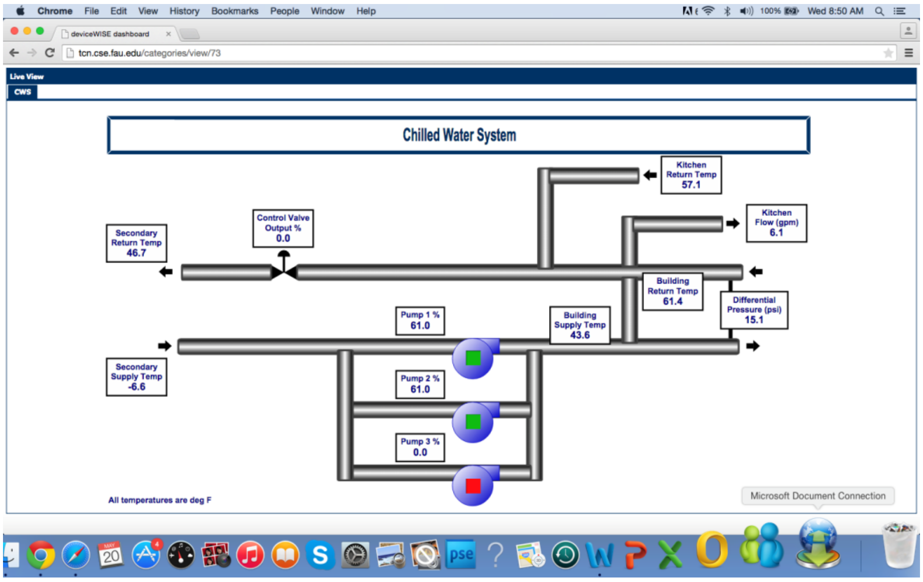
Fig. 3 Dashboard Indicators: on the left is the menu of various views including HVAC Network, Power, and Water systems.

2.1. HVAC system

Unlike traditional cooling systems that use air conditioning system or heat pumps to remove hot air from a building and replace it with cooled air, the system is this building does the opposite. Since on most days in Florida there is a need to cool buildings rather than heat them, a campus-wide chilled water system delivers cold water through the campus. Our building uses an innovative technique to temper the chilled water to reduce humidity, and other systems to heat the building if needed. There are three chilled water tertiary pumps in the building to circulate the chilled water. Two pumps operate in parallel continuously at 50% capacity. The third pump is normally turned off and acts as a back-up to the first two pumps. On a periodic basis, the active pumps are cycled.

As the chilled water arrives in the building some of it is first put through a heat exchanger that increases the temperature of the water by around 10 degrees Fahrenheit. The rest of the water is then piped into the chiller beams in the building and sent to the roof to run through the coils of the air handler units.

Many sensors are installed throughout the system to ensure that all components are working properly. These sensors include the supply and return temperatures at different locations in the building, the output flow and status of the three pumps, the differential and the status of the Chilled Water Control Valve, as shown in Figure 4.



Kitchen Return Temp 57.1

Kitchen Flow (gpm) 6.1

Control Valve Output % 0.0

Secondary Return Temp 46.7

Building Return Temp 61.4

Differential Pressure (psi) 15.1

Pump 1 % 61.0

Building Supply Temp 43.6

Secondary Supply Temp -6.6

Pump 2 % 61.0

Pump 3 % 0.0

All temperatures are deg F

Fig. 4 Chilled water system and relating sensors

The Heating Hot Water System used to heat the building in winter and dehumidify in summer is comprised of three different water system circuits, a Well Water system, a Source Water System and a Hot Water System. The Well Water System pulls water from a well which maintains a constant water temperature of around 78 degrees F. This water is then run through a heat exchanger between the Well Water System and the Source Water System. Depending upon the temperature of the Source Water, the heat exchange either transfers heat energy from the Source System to the Well System or from the Well System to the Source System. The Source Water System runs the water through pipes linked into the computer server room cooling system and absorbs the heat energy from the IT equipment. The water heated by the servers is passed through another Heat Exchange Unit to the Hot Water System on the other side. The Hot Water System then absorbs the heat energy from the Source Water System. If additional hot water is required for dehumidification or heating above what is generated by the computer room servers, the Source Water may also run through one to three heat pumps that extract additional heat from the Source Water and transfer that heat energy to the Hot Water System. The resulting hot water is then sent through the piping system to each floor. There is one additional heat-pump used as a back-up and the order of which heat pump is first, second, third is rotated on a weekly basis.

Sensors record the temperature of the well water, the temperature before and after the first heat exchanger, after absorbing the energy from the servers, and at other spots throughout the building, as shown in Figure 5. Sensors also record the status and operating statistics for the various pumps and heat pumps used in the system.

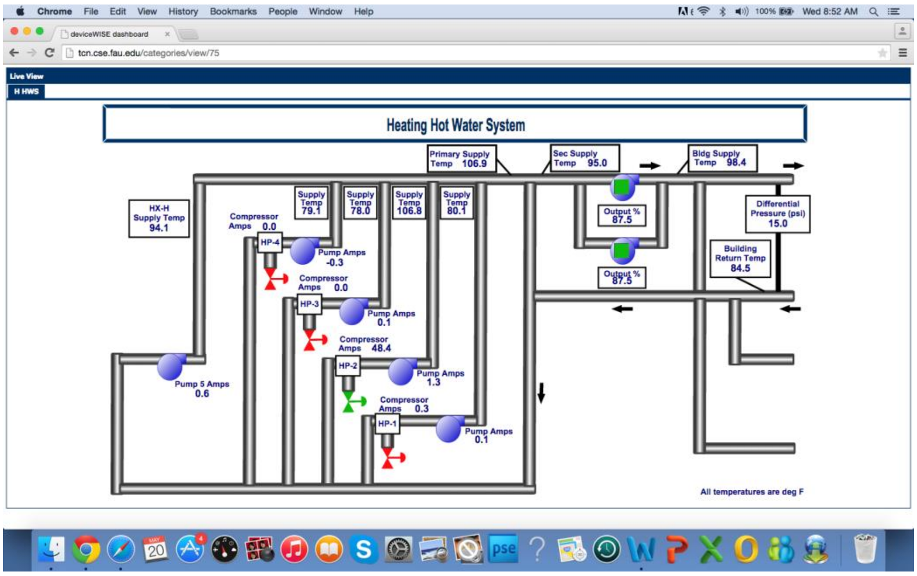


Fig. 5 Heating hot water system and relating sensors

The High Temperature Chilled Water component for air conditioning uses a heat exchange unit to transfer heat energy from a separate water flow to the chilled water system. This results in the separate system maintaining its water temperature at approximately 10F above the chilled water temperature (approximately 55F). The increase in temperature is necessary to reduce the possibility of condensation when the water is run through pipes directly above certain locations. This water is then circulated in separate pipes throughout the building.

The system relies on two pumps with one pump running at a time and the other acting as a back-up. The pump’s responsibilities are swamped each week. The main sensors used by the High Temperature Chilled Water system include the status and output of the two pumps, the temperature of the water entering, after the initial heat exchange, and before the final heat exchange.

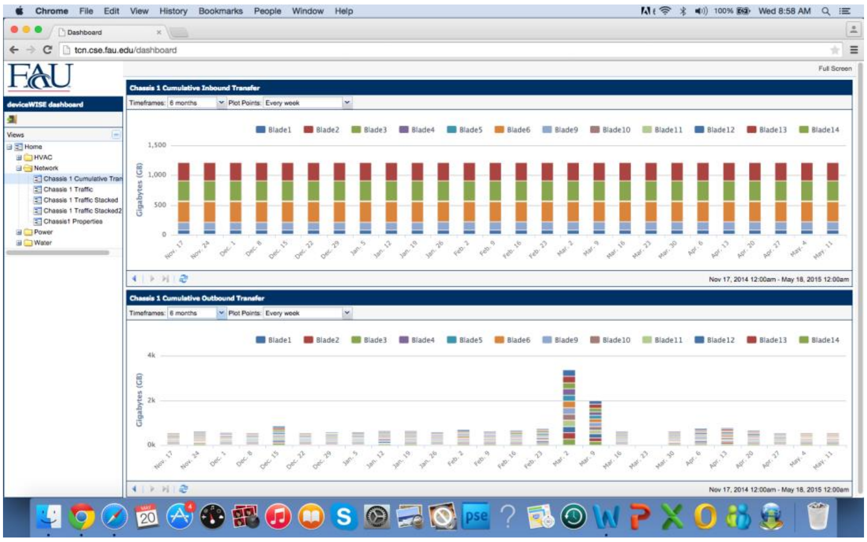
2.2. Engineering server room and cloud computing system

The server room is set up using a “room within a room” (or “hot isle”) configuration. The room itself is a 600 square feet open space cooled by fans blowing over the tempered cold water system. The inner room is comprised of 14 server racks, 4 computer room cooling units and an uninterruptible power conditioning system. The racks and equipment are installed so that they form an enclosed “hot aisle” in about square 300 feet of space.

Fig. 6 (a) The Server room consist of private Cloud Computing System.
(b) Computer laboratory connected to cloud computer using thin clients.

The four computer room cooling units supply additional cooling using a gas to liquid refrigerant configuration. The units remove heat from the “hot aisle” and pass that heat energy through a heat exchanger to the building heating system. The resulting cooler air is blown into the outer room further cooling that space. Server and equipment fans then pull in this cooled air and blow warmer air back into the “hot aisle”.

The server room maintains different type of sensors. One set of sensors captures power data from the four computer room cooling units including the total Amperage for the Supply Fans and Compressors. Several LAN connected temperature and humidity sensors are deployed throughout both the inside room and outside room that provide real-time access to that information. Another set of sensors monitors the LAN traffic flow to and from the servers and power used (in kilowatts) by the servers. The computer system is architected as a private cloud computing system. Two computer laboratories and all computers in the building are using cloud computing technology to run software and access data stored in the cloud computing system (Fig. 6). The cloud computer system consists of 14 blade computers and the network traffic is measured and controlled in real time, as illustrated in Figure 7.



Chassis 1 Cumulative Inbound Transfer

Timeframes: 6 months Plot Points: Every week

Nov 17, 2014 12:00am - May 18, 2015 12:00am

Chassis 1 Cumulative Outbound Transfer

Timeframes: 6 months Plot Points: Every week

Nov 17, 2014 12:00am - May 18, 2015 12:00am

Fig. 7 Network trafic measurements: Cumulative Inbound Transfer

2.3. Building power generation and control

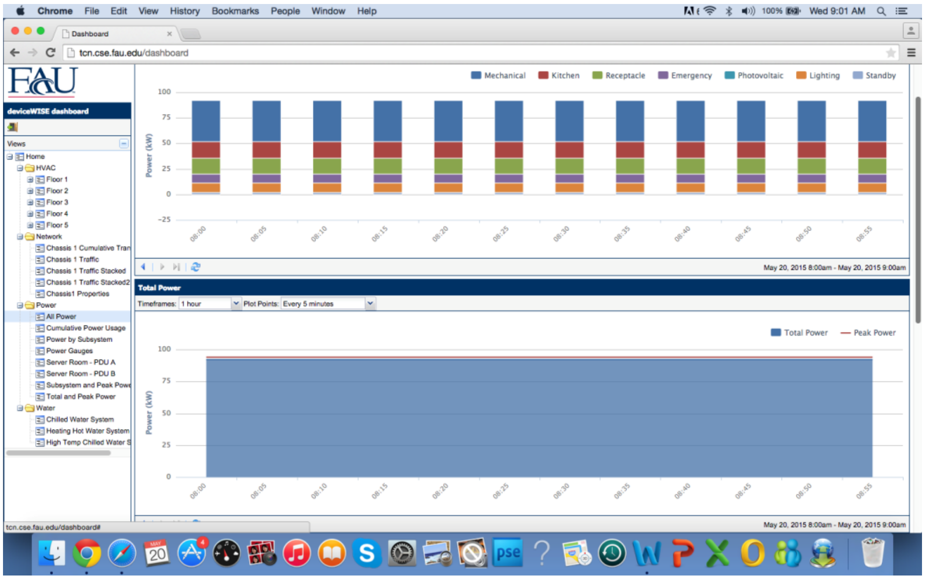
The building generates approximately 4% of its power from three arrays of solar photovoltaic cells. One set of 96 cells is installed on the south-east facing roof of the DaVinci conference center. Two other arrays are installed over the North-South (32 panels) and East-West (48 panels) walkways around the building (Fig. 8). The panels are all rated at 282 watts each which results in a maximum output from all panels with direct sunlight at around 50 kW. The power generated by the solar arrays are routed through a central power conversion unit located in the server room where the direct current from the arrays is converted to alternating current and added to the building's power grid. The converter provides real time reporting of the Watts passed through to the grid.

Fig. 8 Solar photovotalic cells for poer generation

The overall utilization of electricity within the building is monitored by a set of sensors. The utilization is divided into the following categories so that the changes to each system can be analyzed. The categories include:

- Mechanical Equipment – Power used to run the air handler units, pumps, heat pumps, dampers, fans and any other equipment involved in the air conditioning of the building.
- Lights – Power used to light the building.
- Receptacle – Power consumed by any devices plugged into wall receptacles in the building
- Kitchen – Power consumed by the equipment in the kitchen.
- Power consumed by the uninterruptible power supply systems to charge back-up batteries.
- Emergency power, and
- Solar power generated by photovoltaic panels.

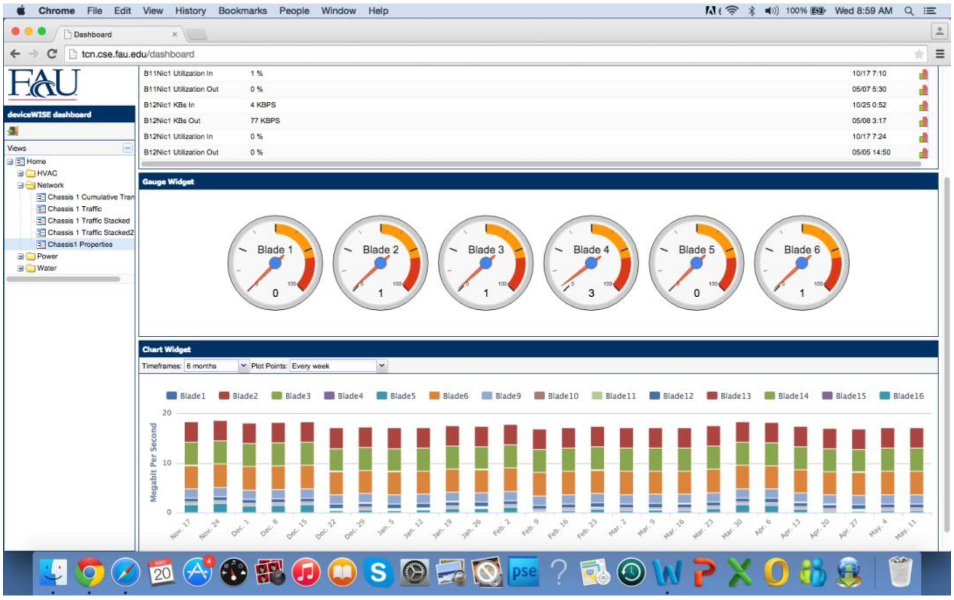
Figure 9 illustrates the cumulative power usage by various subsystems, while Figure 10 shows the real-time network measurements for separate chassis.



Timeframes: 1 hour
Plot Points: Every 5 minutes

Fig. 9 Cumulative power usage by various subsystems

The lights in the building are controlled through a system of linked sensors and switches provided by Encelium Technologies. The lighting system includes both occupied and unoccupied modes for the main hallway lighting, along with overrides based on building occupancy. It relies on sensors and switches installed through the building that determine room occupancy by motion detection and required illumination based on ambient light. The switches allow room occupants to temporarily override normal room lighting.



B11Nic1 Utilization In	1 %	10/17 7:10
B11Nic1 Utilization Out	0 %	05/07 5:30
B12Nic1 KBs In	4 KBPS	10/25 0:52
B12Nic1 KBs Out	77 KBPS	05/08 3:17
B12Nic1 Utilization In	0 %	10/17 7:24
B12Nic1 Utilization Out	0 %	05/05 14:50

Timeframes: 6 months
Plot Points: Every week

Fig. 10 Real-time network measurements for separate chassis.

The system uses a light management application from Encelium named Polaris 3D to optimize the power required for room illumination. The system receives inputs from the various sensors and switches throughout the building, combines that information with configurable lighting parameters then determines the best lighting for each room and each area. It also records lighting and occupancy information for further analysis and research.

3. LIVING LABORATORY: RESEARCH PROJECTS

3.1. Alerting and monitoring system

As part of the NSF Center project, we worked with Aware Technologies and their Process Data Monitor (PDM) system [7], which is an alerting system that uses data mining techniques to categorize sensor data into similar clusters of information. Once these clusters are identified, users can determine whether the clusters represent normal or abnormal running conditions for the sensor data used in creating the cluster. The system will then keep track of the number of times each cluster is computed and when providing an analytical tool to assist in optimization. It will also detect and alert when a cluster is calculated that is outside of the normal operating parameters and report those anomalies through emails. PDM uses a tool named XLReporter to extract information from building sensors and reformat the information into XML files that are then processed by the system.

We also developed data warehouse that stores information from several different sensor systems including Device Wise, standalone wireless and wired sensors, PDM calculated clusters, and weather stations. The collected weather data comes from a link to the WeatherBug API [8] and pulls meteorological information every 15 minutes including temperature, humidity, wind speed and direction, air pressure, rain amount and light levels. The system provides for a set of utility programs that extract the data from the sensors, store it in the FAU “Green” database then summarize and export the information in a variety of different formats for use by other tools such as Weka and Excel.

These systems have been used in several preliminary studies to help validate the data being collected and determine possible future research opportunities. These studies included:

- Determining correlation between photovoltaic energy generation and weather conditions,
- Calculating energy flow between the different components of the air conditioning systems,
- Categorizing cluster data from the PDM system, and
- Determining room occupancy based on room CO2 levels.

3.2. Building power analysis

In this section we present a summary of results we obtained from analyzing the performance of various building systems.

Photovoltaic power system

We analyzed the efficiency of the solar panels by tracking the power generated over a period of one year. Figure 11 shows the solar energy generated per day (in kWh, right *y* axis) in comparison with the total energy consumed by the building systems per day (kWh, left axis), excluding the energy used by IT equipment in the data center.

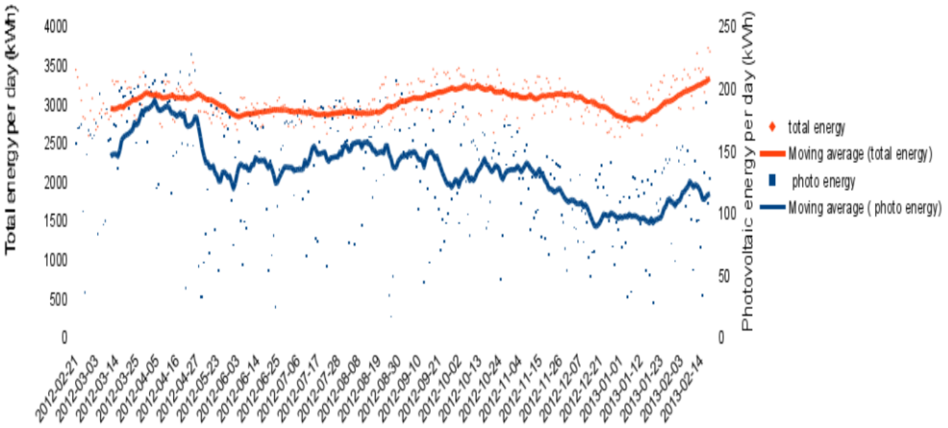


Fig. 11 Photovoltaic energy generated and the total energy used by building systems, including mechanical, receptacles, kitchen, lighting, and standby power.

We noticed a high variation in the solar power generated; this is due mainly to variable day by day cloud coverage. Between March and May it was a period of very clear skies with almost no rain and hardly any clouds. Conversely, at the beginning of 2013 it was a period of high cloud coverage combined with the shorter day time that caused reduced solar energy generation. The total energy consumed by building systems, in orange color, depends on building occupancy, with lower consumption during school breaks in March, June-August, for Thanksgiving (end of November), and the winter break. A summary of the energy statistics are listed in Table 1. The solar energy produced is on average 4.45% of the total energy used by building systems and has a high standard deviation – 1/3 of the mean.

We built a predictive model with the Weka tool for the solar power having the time of day, outside temperature, light-level %, humidity %, and rain as attributes. A REPtree decision tree algorithm achieves the lowest relative absolute error of 19.26% among all alternatives, and a mean absolute error of 1.38 (kW), with a correlation coefficient of 93.9%. The solar power prediction error is caused by measuring the light level from a meteorological station located 4 km from the building; clouds passing on cause a variable delay in measuring light levels.

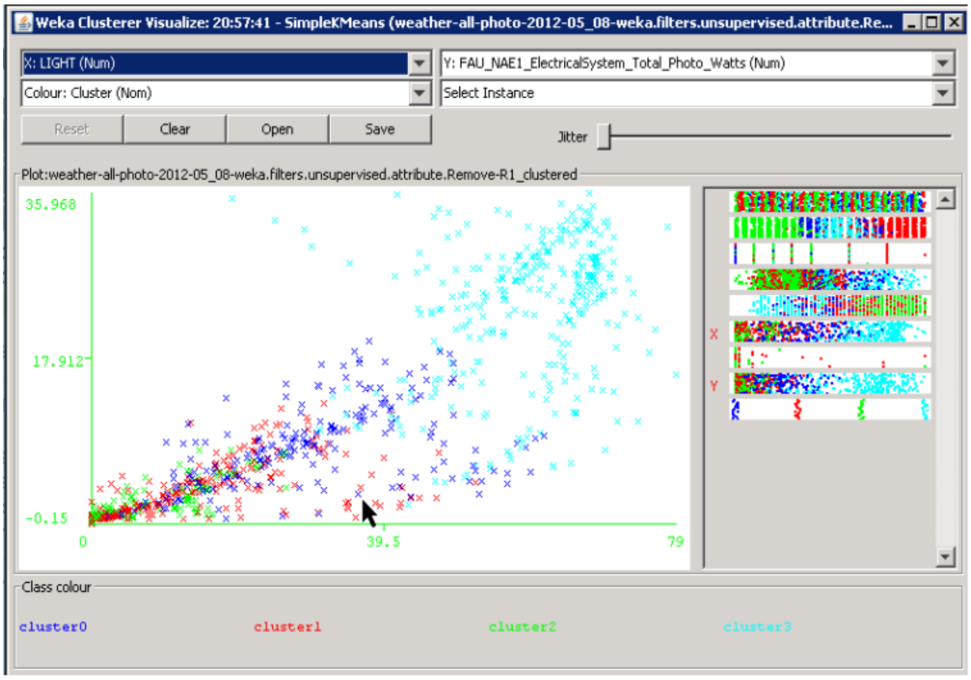
Table 1 Summary statistics for the solar energy produced and the total energy consumed during 1-year period.

	Photo energy per day (kWh)	Total energy per day (kWh)	Photo / Total %
Maximum	227.05	3720.83	7.60%
Minimum	16.53	2575.42	0.60%
Average	134.55	3030.52	4.45%
Stdev	45.84	223.83	1.54%

The solar energy produced is on average 4.45% of the total energy used by building systems and has a high standard deviation – 1/3 of the mean.

We built a predictive model with the Weka tool for the solar power having the time of day, outside temperature, light-level %, humidity %, and rain as attributes. A REPtree decision tree algorithm achieves the lowest relative absolute error of 19.26% among all alternatives, and a mean absolute error of 1.38 (kW), with a correlation coefficient of 93.9%. The solar power prediction error is caused by measuring the light level from a meteorological station located 4 km from the building; clouds passing on cause a variable delay in measuring light levels.

A k-means clustering algorithm applied to the same photovoltaic data model yields the clusters seen in Figure 12. The relation between the *light* value and the solar power generated is disturbed by the aforementioned measurement delay and by the orientations of the solar panels that don't match the normal orientation of the light sensor.



Weka Clusterer Visualize: 20:57:41 - SimpleKMeans (weather-all-photo-2012-05_08-weka.filters.unsupervised.attribute.Re...

X: LIGHT (Num)

Y: FAU_NAE1_ElectricalSystem_Total_Photo_Watts (Num)

Colour: Cluster (Nom)

Select Instance

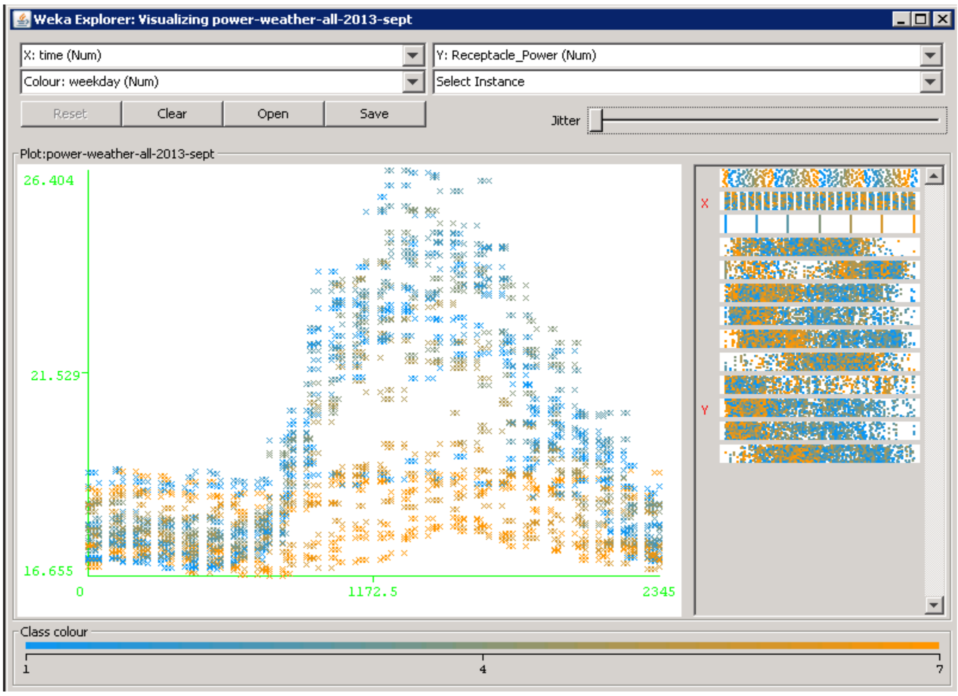
Plot:weather-all-photo-2012-05_08-weka.filters.unsupervised.attribute.Remove-R1_clustered

Fig. 12 Dependence of the photovoltaic power (vertical axis) of the light level (horizontal axis). Instances are color-coded according to classes determined by the k-means clustering algorithm.

Prediction models for receptacle power

Receptacle power in the building is used by anything plugged into a power outlet. This depends in part on the building occupancy, as office equipment (e.g. laptops) is a major consumer. Figure 13 shows the dependence of the receptacle power (vertical axis, in the 16.6-26.4 kW interval) on the time of day (0-2400), as measured for the Sept. 2013 month.

The power rises sharply after 8AM, peaks at 1PM, then drops gradually after 4PM until 11PM. The points in brown represent measurements taken during the weekend, with a lower power value. The weekend peak is 19 kW, the weekday peak (on Wednesday at 1PM) is 26.4 kW, while at night the power drops to 16.9 kW. The chart also partitions the measurements into 7 clusters determined by the k-means algorithm. A M5 decision tree classifier computed with Weka has a relative absolute error of 36.15%, a mean absolute error of 0.6837, and a correlation coefficient of 92.31%. For training and evaluation in all experiments we used 10-fold cross validation and we searched for the lowest error.



Weka Explorer: Visualizing power-weather-all-2013-sept

X: time (Num)

Y: Receptacle_Power (Num)

Colour: weekday (Num)

Select Instance

Fig. 13 Weka screenshot showing the dependence of the receptacle power on the time of day (0 – 2400) and 7 clusters computed using k-means algorithm.

Data center power

The data center consists of two racks located in a “hot isle” enclosure, with separate uninterruptible power supply units used by computing blades, discrete PCs, network attached storage, and networking equipment. The total power used by the data center includes that used by the four CRAC (air conditioning units) that cool the air inside the hot isle. The total data center power has grown in small chunks due to additions and upgrades to equipment, from 277 kW, in 08/2012, to 368 kW, in 10/2013. The total power has a standard deviation during a day and during a week of about 1.1% of the average for the corresponding period. The hot water circuit that extracts heat from the hot isle using heat pumps achieves a high temperature of 50°C and a maximum differential of 20°C, proving effective in reusing waste heat for other building systems.

4. CONCLUSIONS

Strong instrumentation in the new LEED Platinum engineering building opens up a multidimensional view of the inner working of its HVAC and power systems. A variety of sensors allow a detailed analysis of the building system performance and the data center power utilization. However, it is equally important to consider external variables, such as weather, building occupancy, and school schedule to get a more accurate picture.

Our analysis found that the solar power generated covers a maximum of about 7.6% and 4.65% on average of the total building-related energy consumption and that it varies highly with cloud coverage. Another interesting observation is that the total power used by the building (122 kW on average for 09/2013) is 2.79 times smaller than the power consumed by the data center (average of 341 kW). Still, this figure does not include most of the power needed for cooling the building, as it is spent by the chilled water campus plant. In the future we will conduct more analysis aiming to estimate power savings from cooling in the data center by raising the hot isle temperature.

Acknowledgement: *The paper is a part of the research done within the project funded by NSF - Industry/University Cooperative Research Center for Advanced Knowledge Enablement, 2009-2020.*

REFERENCES

[1] D. Sciuto and A.A. Nacci, "On How to Design Smart Energy-Efficient Buildings," In Proceedings of 12th IEEE International Conference on Embedded and Ubiquitous Computing, Milano, Italy, 2014, pp. 205-208.
[2] "Special Section on Intelligent Buildings and Home Energy Management in a Smart Grid Environment," IEEE Transactions on Smart Grid, Vol. 3, No. 4, December 2012.
[3] O. Evangelatos, K. Samarasinghe, and J. Rolim, "Evaluating Design Approaches for Smart Building Systems," In Proceedings of the 9th International Conference on Mobile Adhoc and Sensor Systems, Las Vegas, Nevada, 2012, pp. 1-7.
[4] Y. Sun, T-Y. Wu, G. Zhao, and M. Guizani, "Efficient Rule Engine for Smart Building Systems," *IEEE Transactions on Computers*, Vol. 64, No. 6, pp. 1658-1669, June 2015.
[5] R. Fantacci, T. Pecorella, R. Viti, C. Carlini, and P. Obino, "Enabling Technologies for Smart Building, What's Missing?", In Proceedings of the AEIT Conference, Mondello, Italy, 2013, pp. 1-5.
[6] S. Tadokoro et al, "Smart Building Technology," *IEEE Robotics & Automation Magazine*, Vol. 21, Issue 2, 2014, pp. 18-20.
[7] Aware Technologies, Process Data Monitor (PDM), http://awaretechnology.com/.
[8] WeatherBug API, http://weather.weatherbug.com/desktop-weather/api-documents.html.