

## ENERGY MODELING AND CALIBRATION OF A MIXED-USE BUILDING WITH LABORATORIES, OFFICES AND CLASSROOMS

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### ABSTRACT

In general, mixed-use buildings with laboratories, offices, and classrooms consume significant energy and are very energy intensive. These buildings provide great opportunities for energy efficiency improvement from mechanical and energy systems. However, the interconnected complexity of system and equipment in buildings with laboratories makes modeling of these buildings a unique and challenging task. This paper presents the development and calibration of a university mixed-used building using the EnergyPlus simulation program. The building under study is the South Engineering Research Center (SERC) building. Air Handler Units (AHU) equipped with Energy Recovery Units (ERU) supply 100% outside air to the laboratory spaces through terminal Variable Air Volume Boxes (VAV). Chilled water and hot water are delivered from the campus central energy plant. The modeling process, preliminary calibration, and verification results, as well as implementation issues encountered throughout the modeling and calibration processes from a user's perspective, are presented and discussed.

### INTRODUCTION AND BACKGROUND

Whole building energy simulation becomes more and more popular for research and actual world applications, not only in the design phase but also in the post-construction phase (Augenbroe 2002). Green building certificate requires building energy performance modeling, such as LEED (Leadership in Energy and Environmental Design) is used by more building owners in the U.S. Whole building energy simulation plays a significant role in the process of green building certificate and building operation management. During the design phase, to have an energy efficient building, it is beneficial to evaluate different design options based on energy consumption estimated from the building simulation. Recently, more and more researchers and practitioners started to use building simulation in the post-construction phase. This includes model-based commissioning, model-based energy diagnostics, model-based control, etc.

Based on the study of Karlsson et al. (2007), Turner and Frankel (2008), and Scofield (2009), the difference between simulation results and the actual meter readings could be up to 100% or more. One of the reasons is that certain degrees of assumptions were made during the modeling process due to the availability of the building and equipment information. Besides some necessary assumptions, Tupper et al. (2011) stated there was a lack of standard procedure while creating and calibrating building energy models. Thus, to have an accurate building energy model, it is necessary to do some calibrations and tuning the model. Tuning the model to minimize the discrepancies between energy usage estimation from building simulations and measured building energy usage is called calibration (Fabrizio and Monetti 2015).

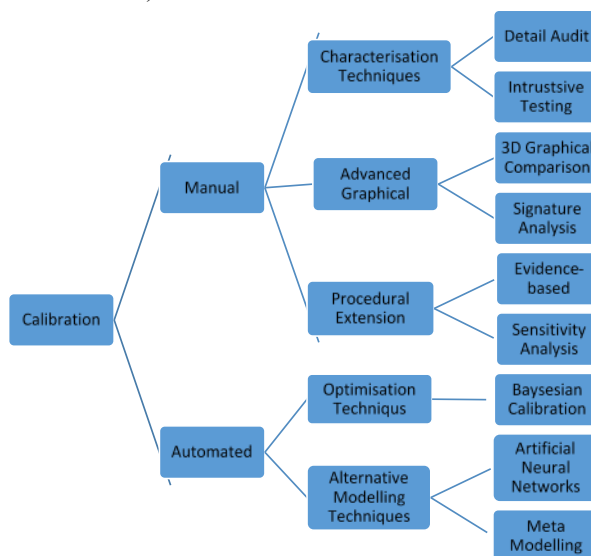


Figure 1: A summary of calibration approaches  
Coakley et al. (2014)

Coakley et al. (2014) had a comprehensive review of the modern calibration method. Figure 2 shows the relationship of the calibration approaches and some common examples. In their review, calibration approaches were classified into two main categories,

manual and automated. A manual approach consists of characterization techniques, advanced graphical approaches, and procedural extensions. An automated calibration needs some optimization techniques. Approaches like sensitivity analysis (SA), optimization techniques and Meta-modelling need complicated mathematical algorithms either to find the key parameters or determine the cost or penalty function, etc. (O'Neill and Eisenhower 2013). Usually, those methods would be used in the scientific research study but not in the practical applications as for now (Coakley et al. 2011). For example, artificial neural network (ANN) approach is an approach used for model calibration, but it needs a large number of historical data to form the baseline performance. Neto and Fiorelli (2008) concluded that even though an EnergyPlus model calibrated using ANN approach matched measurements well in their study, it is only capable of estimating the energy usage based on a large number of measurements. Model calibration of new buildings with limited data sets is challenged using ANN approach.

Evidence-based calibration approach could be an effective method because such approach has the reproducibility when any change to the model input parameters is made according to available evidence (Raftery et al. 2011). Raftery et al. (2011) performed an evidence-based methodology that was partially adopted into the case study presented in this paper. After the preparation stage, data and information through a detailed energy survey and walk-through the buildings are necessary for the model inputs calibration and tuning.

One of the difficulties to apply building energy simulation to the post-construction stage is that there is less degree of freedom to manipulate the simulation in the post-construction phase than the design phase because most of the input parameters have true values. Estimating energy savings potential from different operation strategies and understanding the operation behavior of buildings in the post-construction phase would be an area of the study. This paper focuses on a building in the post-construction stage. This building is Southern Engineering Research Center, a mixed-use building with laboratories, offices, classrooms, etc. For this study, evidenced-based approach with detail energy audit was selected as the primary method. Other approaches were not selected mainly due to the complicity of algorithms, availability of data, and the time limit for the project. Ongoing and future work includes sensitivity analysis based auto-tuning.

## METHODOLOGY

Building under this study is the South Engineering Research Center (SERC), and it has been occupied since January 2012. SERC is a mixed-use three-story campus building with laboratories, classrooms, conference rooms, auditoriums, and offices. The total area of the building is 16,300 square meters. It contains 40 research and instructional labs and 38 faculty and staff offices along with about 145 graduate students' working space.

It is one of the most frequently used facilities among other engineering buildings. Figure 2 is the site view of SERC and the 3D model built by DesignBuilder.



*Figure 2: The site view of SERC building*

The major HVAC system in SERC consists of 11 variable air volume (VAV) AHUs that serve the building, and 165 VAV boxes with reheat hot water coils at the zone level. SERC is divided into three sections: North Section, West Section, and South Section. North Section primary air conditioning system contains four AHUs and two ERUs. West Section primary air conditioning system contains three AHUs and two ERUs. South Section primary air conditioning system has four AHUs and three ERUs. Each AHU includes a water cooling coil, a water heating coil, and a variable speed fan. The design AHU discharge air temperature is 12.8 degrees Celsius. Figure 3b is a schematic diagram of AHUs serving North Section, and the other two sections have a similar configuration. As shown in Figure 3b, AHUs with the same capacity and size are in parallel. However, EnergyPlus version (version 8.2) used for this study is not capable of modeling this configuration. Therefore, an artificial AHU with a doubled capacity is created to mimic AHUs in parallel.

Chilled water and hot water are supplied from the central energy plant on campus, as shown in Figure 3a. As described in the design document, two parallel chilled water pumps at the building bridge level deliver 7.2 degrees Celsius chilled water to the building. Hot water at 107.2 degrees Celsius is supplied from the campus energy plant to two water-to-water heat exchangers. Then, hot water at 82.2 degrees Celsius is pumped to the building. Two heat exchangers are connected in parallel. Each heat exchanger connects with a variable speed hot water pump.

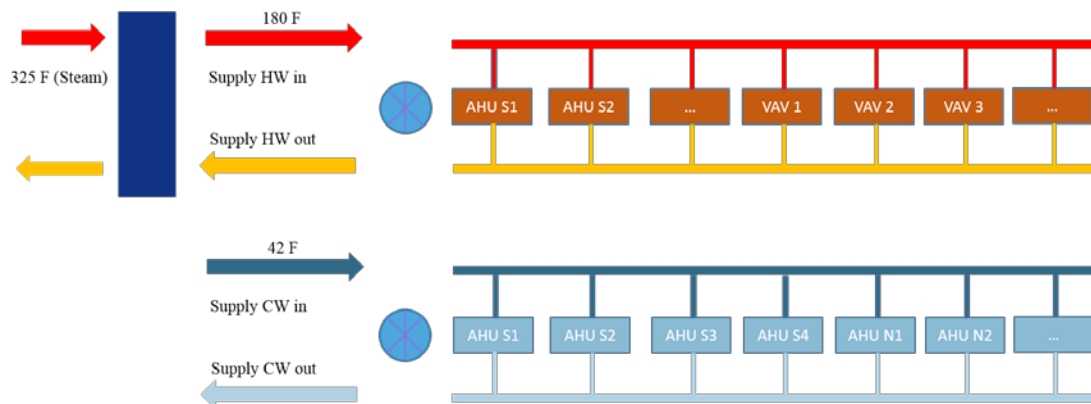


Figure 3a: SERC north section HVAC schematic: waterside

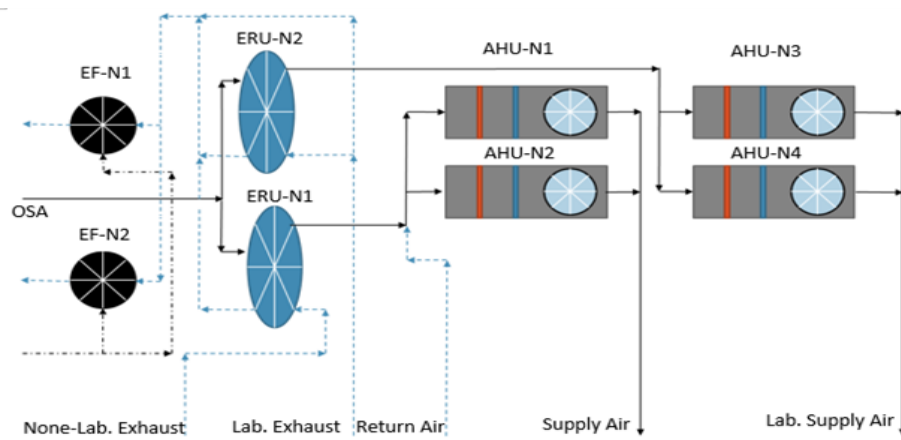


Figure 3b: SERC north section HVAC schematic: airside

An EnergyPlus (version 8.2) model was developed for SERC to predict the annual energy consumption and the prediction was compared with the actual energy bill. The building model was first created in DesignBuilder and then exported to EnergyPlus IDF editor. Building geometry modeling is based on AutoCAD drawing. At this step, building envelope physical information including wall composition, thickness, and thermal and optical properties was captured and inputted to the DesignBuilder. The model with building geometry was exported to EnergyPlus IDF editor for adding building operation schedule, internal heat gains, and HVAC equipment and system. Information such as internal plug loads, occupancy, room air temperature set points, lighting power density, and operation schedule is collected through a building walk-through. Figure 4 illustrates the modeling and calibration process used in this case study.

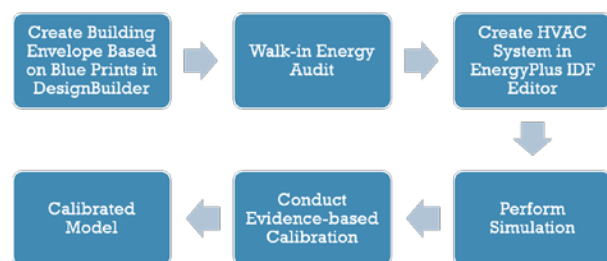


Figure 4: Building modeling process flow chart

Local weather data, including dry bulb temperature, humidity ratio, solar radiation flux, etc., was collected by HOBO U30 weather station on campus, as shown in Figure 5.



Figure 5: On-site weather station

The comparisons of TMY3 data and real-time measurement in January and August in 2014 are shown in Figure 6. A significant difference in temperatures can be observed.

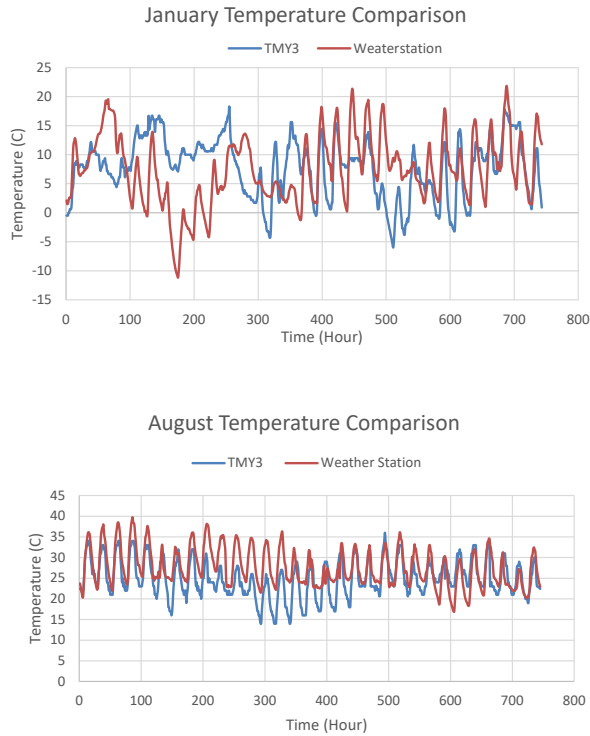


Figure 6: Local and TMY3 temperature comparison

EnergyPlus has a preferred weather data format, which requires a conversion from original weather data collected by HOBO weather station. The weather data from the on-site weather station has a sampling frequency of two minutes, and it was converted into hourly data. Furthermore, the weather station only has the global horizontal radiation. However, EnergyPlus requires both direct normal radiation and diffuse horizontal radiation components. In this study, Maxwell

DISC (Direct Isolation Simulation Code) method of decomposition of light was performed (Maxwell 1987) to decompose the measured global horizontal radiation to the direct normal radiation and the diffuse horizontal radiation. The diffuse horizontal radiation estimation process is shown in Figure 7.

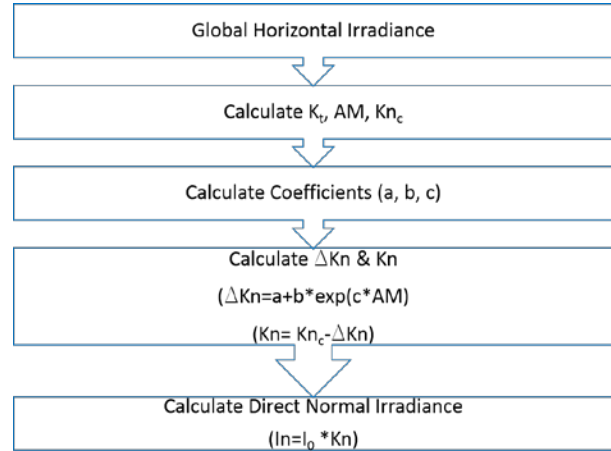


Figure 7: Weather file solar radiation process chart

The diffuse horizontal radiation estimation are calculated using the following equations.

Clearness Index is defined by Equation (1)

$$K_t = \frac{I}{I_0 \cos(\theta)} \quad (1)$$

Air mass is calculated by Equation (2)

$$m_{air} = [\cos(\theta) + 0.15(93.885 - \theta)^{-1.253}]^{-1} \quad (2)$$

Maximum of sky clearness index is derived by Equation (3):

$$K_{nc} = 0.866 - 0.122m_{air} + 0.0121m_{air}^2 + 0.000653m_{air}^3 + 0.000014m_{air}^4 \quad (3)$$

The  $\Delta K_n$  is calculated based on the values of  $K_t$ , Equation (4), Equation (5), and Equation (6):

$$\Delta K_n = a + be^{cm_{air}} \quad (4)$$

if  $K_t \leq 0.6$ ,

$$\begin{cases} a = 0.512 - 1.56K_t + 2.286K_t^2 - 2.222K_t^3 \\ b = 0.37 + 0.962K_t \\ c = -0.28 + 0.932K_t - 2.048K_t^2 \end{cases} \quad (5)$$

if  $K_t \geq 0.6$ ,

$$\begin{cases} a = -5.743 + 21.77K_t - 27.49K_t^2 + 11.56K_t^3 \\ b = 41.4 - 118.5K_t + 66.05K_t^2 + 31.9K_t^3 \\ c = -47.01 + 184.2K_t - 222K_t^2 + 73.81K_t^3 \end{cases} \quad (6)$$

Direct transmittance is calculated by Equation (7):

$$K_n = Kn_c - \Delta K_n \quad (7)$$

Direct normal radiation is found by Equation (8):

$$I_n = I_0 K_n \quad (8)$$

Diffuse horizontal radiation can be found by Equation (9):

$$I_d = I - I_n \sin(\theta) \quad (9)$$

Following this procedure, a 2014 local EnergyPlus weather data (EPW) file was generated and used for simulations. An evidence-based calibration was

performed. According to Coakley et al. (2011) and Raftery et al. (2011), the origin of parameters source could have effects on the accuracy of the simulation. Design stage information is the least preferred parameters source. Thus, more reliable data source, such as the data from building energy management system (BEMS), need to be obtained. Using the data from real-time measurements and site surveys should lead to more accurate simulation results (Coakley et al. 2011; Raftery et al. 2011). In this study, HOBO temperature and occupancy sensors were also placed into office and classroom for a better understanding of room temperature control and occupancy. The occupancy sensor measures light intensity. Figure 8 shows the occupancy and temperature plot for one classroom in the SERC.

A summary of the changes made to the EnergyPlus model is shown in Table 1.

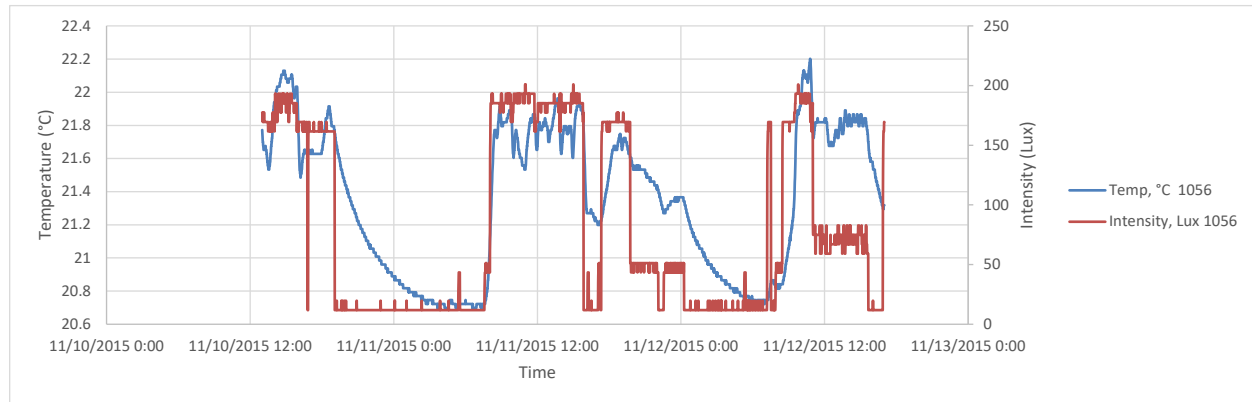


Figure 8: HOBO sensor zone temperature and light intensity for classroom 1056

Table 1. Primary changed parameters and source

Component	Before Calibration	After Calibration	Source
AHU Supply Air Temperature	12.8 °C	12 °C	BEMS
Infiltration Rate	0 ACH	0.4 ACH	ASHRAE Handbook
Hot Water Pump Flow Rate	0.05 m <sup>3</sup> /s	0.1 m <sup>3</sup> /s	Design drawing
Chilled Water Pump Flow Rate	0.068 m <sup>3</sup> /s	0.138 m <sup>3</sup> /s	Design drawing
Hot Water Min Temperature	37.8 °C	54.4 °C	BEMS
Chilled Water Min Temperature	0 °C	4.4 °C	BEMS
Exterior Light Power	0 W	10000 W	Survey
Number of People in Summer	800	400	Survey

Table 2. Scale factor used in this study

Object	Factor
Electricity	2.34
Hot Water	1.25
Chilled Water	1.45

Table 3.2 Calibration criteria recommended by ASHRAE Guideline 14

Guideline	Monthly criteria (%)	
	NMBE	CV-RMSE
ASHRAE Guideline 14	5	15

Table 4.3 SERC EnergyPlus model CV-RMSE and NMBE using 2014 monthly utility bill

Energy Sources	CV-RMSE (%)	NMBE (%)
Electricity	10.97	4.86
Hot Water	14.61	-3.41
Chilled Water	13.00	-0.461

## RESULTS

Simulation results were scaled to include the energy consumption from the combustion lab which was located in the south side of the SERC. Due to the complexity of the combustion lab HVAC system, this lab and associated HVAC system were not modeled in this study. The scale ratio was calculated based on the HVAC design capacity ratio of the total SERC and the combustion lab. The scale factor is listed in Table 2.

To validate the simulation result, ASHRAE Guideline 14 (ASHRAE 2002) was used as the reference and criteria for the evaluation. ASHRAE Guideline 14-2002 recommends an acceptable accuracy for whole building energy model in terms of CV-RMSE and NMBE. The coefficient of variation of root mean square error (CV-RMSE) and normalized mean bias error (NMBE) are calculated using model estimations ( $\hat{y}_i$ ) with measured utility data ( $y_i$ ). CV-RMSE shows the variability of the errors between the estimated and measured values. It “gives an indication of the model’s ability to predict the overall load shape that is reflected in the data” (Granderson et al. 2015). A lower CV-RMSE indicates a less variance of the RMSE and hence a higher accuracy. NMBE is a normalization of MBE, which can be used to make MBE comparable. NMBE is known to be subject

to cancellation errors. Therefore, the use of NMBE alone is not recommended.

CV-RMSE and NMBE are commonly used to evaluate the agreements between the model estimations and actual measurements. Table 3 listed the calibration criteria recommended by ASHRAE Guideline 14 (ASHRAE 2002).

CV-RMSE is determined using Equation (10)

$$CV - RMSE = \frac{100 \times \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n-1}}}{\bar{y}_i} \quad (10)$$

NMBE is determined using Equation (11)

$$NMBE = \frac{\sum (y_i - \hat{y}_i)}{(n-1) \times \bar{y}} \times 100 \quad (11)$$

The SERC energy sources include electricity, chilled water, and hot water. Both chilled water and hot water energy consumptions are metered through thermal BTU meters. The EnergyPlus simulation used a time step of 15 minutes and 2014 real-time weather data, which was collected and converted from an on-site weather station.

Table 4 presents the CV-RMSE and NMBE values for the SERC EnergyPlus model using the 2014 monthly utility bill. These results show that the simulation



estimations for all three energy sources meet the recommended CV-RMSE and NMBE in ASHRAE Guideline 14-2002 for the monthly bill.

Figure 9 shows monthly comparisons between EnergyPlus model predictions and the 2014 utility bill for SERC electricity, hot water, and chilled water consumption. It shows the calibrated energy model is capable to predict whole year building energy consumption. There is a noticed difference between the prediction and measurements for February 2014. It is likely due to differences in HVAC operation schedules, class schedules, etc. between the model and the reality. Current SERC EnergyPlus model does not have different HVAC operation schedules for individual month. Instead, HVAC schedules were set up following seasonal variations (i.e., summer vs. winter). We will investigate whether monthly HVAC schedules tuning will further improve the model estimation performance.

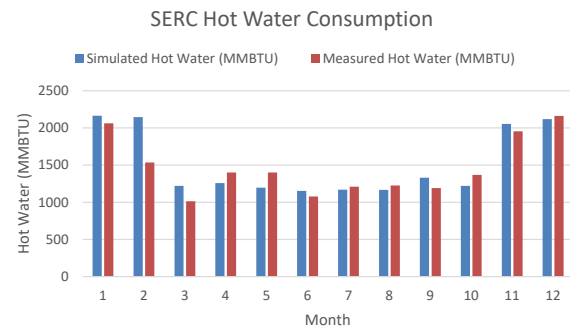
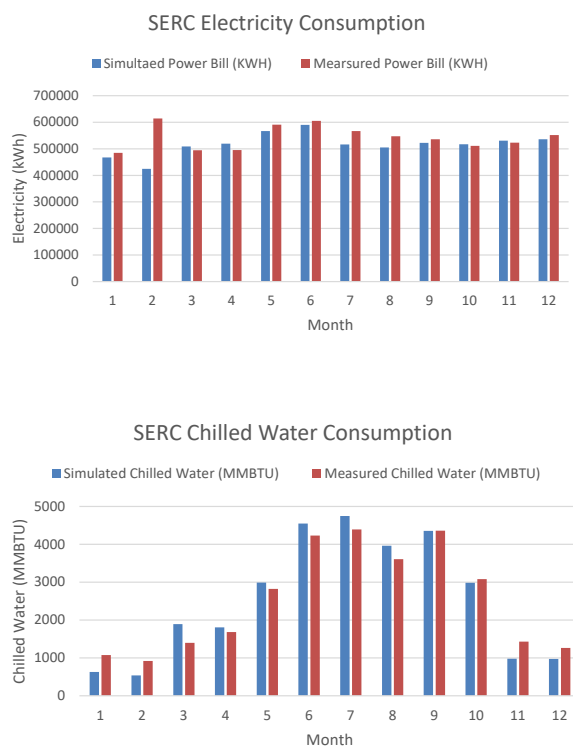


Figure 9: SERC EnergyPlus model and utility bill comparison

## CONCLUSIONS

Regarding comparisons with the monthly utility bill, simulation results for electricity, chilled water, and hot water energy consumption all meet the criteria from ASHRAE Guideline 14. There are still some differences between measurements and model estimations. Several concerns could be brought up and considered as the reasons for such differences.

- First of all, the actual zone occupancy was very difficult to be captured. SERC is one of the most used facilities for engineering and science students. Internal heat gains could lead a difference in the energy balance in each thermal zone. Class schedule, laboratory course schedule, and faculty office occupancy could be different for every semester. It is difficult to accurately capture occupancy schedule in a building energy modeling because of a stochastic nature of occupant behaviors. Although some surveys have been conducted, actual occupancy schedule still could be different. The difference between actual and assumed occupancy schedules would lead to less accurate simulation results.
- Second, facility operation schedule may change. For the design condition, all AHUs and their water coils operate all the year round, which is the current setup in the EnergyPlus model. From the observation in the spring 2016, chilled water was not delivered to SERC for a couple of days.
- Third, actual building envelope may be different with that from the design stage. Building envelope plays an important role in the heat balance calculation between the outside and the inside of the building. Current SERC EnergyPlus model is using the building envelope information from the design drawings. It is possible that the actual building

material could be changed during the construction stage.

- Fourth, water coil efficiency may be different or changed. Water coils parameters that were input to EnergyPlus model was based on the design condition. As water coils getting old, their heat transfer efficiency may be changed as well. With the assumed water coil efficiency, it could have some impacts on the model accuracy.

SERC is a complex building with more than 3,000 parameters in the EnergyPlus model. In this EnergyPlus model, all the assumptions and uncertainties will be accumulated, which raises the importance of sensitivity study to find the influential rank for the parameters. Ongoing and future work includes sensitivity analysis based calibration. This study generated a reasonable energy performance model that could be used for model-based studies. The behavior of this model will be further investigated and improved in the future. Calibrations with the hourly meter data will be investigated as well.

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## NOMENCLATURE

$y_i$ : measured utility data

$\hat{y}_i$ : simulation data

$n$ : the number of data points in the baseline period  
 $n=12$  the monthly data

$\bar{y}$ : the arithmetic mean of the sample of  $n$  observations.

$I$ : global horizontal radiation ( $\text{W/m}^2$ )

$I_n$ : direct normal radiation ( $\text{W/m}^2$ )

$\Theta$ : sun's zenith angle ( $^\circ$ )

$K_{nc}$ : maximum of sky clearness index

$K_n$ : direct radiation transmittance

$I_0$ : solar constant, which is  $1370 \text{ W/m}^2$

$I_d$ : diffuse horizontal radiation ( $\text{W/m}^2$ )

$m_{air}$ : Air mass

$K_t$ : clearness index

CV-RMSE: coefficient of variation of root mean square

NMBE: normalized mean bias error