A CASE STUDY IN ACTUAL BUILDING PERFORMANCE AND ENERGY MODELING WITH REAL WEATHER DATA

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Abstract

Building energy simulation is a critical component in the process of designing an energy efficient building to predict annual energy consumption. Majority of these buildings, however, have what is known as a performance gap where the building consumes more energy than originally predicted. In order to analyze the potential performance gap, a case study approach has been adopted. This paper seeks to answer how does actual energy consumption of a University Building compare with energy consumption prediction using eQuest? The results show that the predicted electricity consumption to be within 0.72% of actual on an annual basis. However, natural gas consumption is more erratic and has fluctuating monthly differences, with an overall annual average ranging, 4.5% to 16%. Areas future work would seek to gather data over a longer period and install a weather station on the building to generate site-specific weather data.

1 Introduction

It is a general knowledge that the current building population consumes a larger portion of the energy produced. In 2010 the commercial building sector consumed about 30% of the total electrical and about 21% of the natural gas produced in Canada (Natural Resoure Canada 2011). Leadership in Energy and Environmental Design (LEED) is one of the most popular optional rating systems aiming to reduce energy consumption of buildings.

In order for a building to be certified under LEED, the design team has to generate a base line model in accordance with ASHRAE Standard 90.1 or Model National Energy Code for Buildings (MNECB). In doing so, the projected savings for the proposed design may be established (U.S. Green Building Council 2010). Despite efforts to accurately predict energy consumption pre-construction, there is a significant gap between predicted and actual energy consumption. This has brought about the term known as performance gap with efforts being made to reduce this discrepancy (Carbon Trust 2011). The performance gap is not an issue present in all buildings but is an area of concern. As part of this report, the actual versus predicted energy consumption of the Undisclosed University Building (UDUB) will be evaluated. In order to accurately represent the building, eQUEST modeling tool will be utilized in conjunction with actual weather data collected from weather station Hamilton A between January 2011 and March 2013.

2 Literature Review

Energy Audits

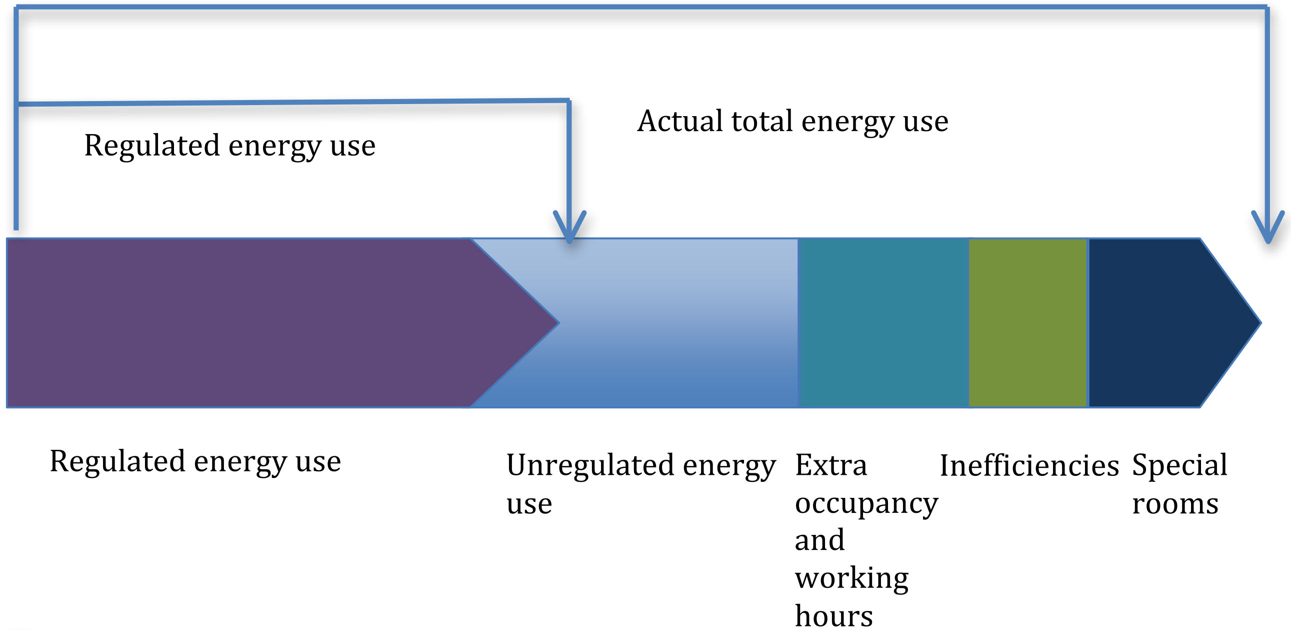
In performing the literature review a number of research articles, reports and studies were reviewed to understand why buildings are not performing as intended and what steps can be taken to create a more robust energy model. The focus is primarily on commercial buildings pertaining to their performance, factors of influence over energy consumption and ability to simulate their daily operations.

A number of studies have been conducted over the years to evaluate the performance of energy efficient buildings. The PROBE (Post-occupancy Review of Buildings and their Engineering) study evaluated 23 energy efficient buildings over a span of seven years. Results indicated energy consumption was generally higher than anticipated due to sources such as, computer labs and office equipment adding 25% to 80% to the total building energy consumption (Bordass et al. 2001). Many of the inaccuracies stemmed during the modeling phase due to unrealistic assumptions (Bordass et al. 2001). Figure 1 demonstrates where the performance gap originates from, due to simplification and discounting inefficiencies that may occur within commercial buildings (Carbon Trust 2011).

In the early 80's it was understood that energy models inputs were based on very best energy behavior and rule out tenant lifestyle and operational inefficiencies (Norford et al. 1994). Despite the industry having an early understanding of the shortfalls of energy prediction and sources of inaccuracies, today's energy efficient buildings are still challenged by this.

Two similar studies conducted evaluated the post-occupancy energy performance of LEED buildings within the United States (Oates & Sullivan, 2012; Turner, 2006). From the surveyed buildings no single building's actual energy use intensity is within 20% of the projected savings demonstrated from the proposed design model (Turner 2006). Results demonstrated that of the 19 buildings sampled by Oates and Sullivan's, "four of the high energy intensity buildings performed 48% worse than the design case and 24% worse than the baseline model". "The 15 buildings of medium energy intensity underperformed the design model by 74% and the baseline model by 14%" (Oates & Sullivan 2012). It must be noted that as many of the commercial buildings get bigger heat loss/gain for heating and cooling will become smaller in comparison to other end uses like plug loads, lighting, and ventilation.

Caution must be drawn from the two studies, not all of the samples for the LEED buildings were randomized and some were dependent on voluntary information prepared by the owner. The studies are limited because they examine a very small population of the total energy efficient buildings currently on the market.



- 🟪 Regulated energy use includes heating, hot water, cooling, ventilation and lighting
- 🟦 Unregulated energy use includes plug loads, security, external lighting, and elevators
- 🟦 Extra occupancy, equipment and additional operating hours (i.e. evenings and weekends)
- 🟩 Inefficiencies from poor controls, improper commissioning and lack of maintenance
- ⬛ Special function (separate energy uses) including server rooms, cafeteria and emergency energy

Figure 1 Predicted energy vs. actual total energy use (Carbon Trust 2011)

Accuracy of simulation tools

It is still unclear whether modeling tools can accurately predict total energy consumption of a building within an acceptable error margin. Menezes, Cripps and Buswell seek to understand this question by utilizing post occupancy evaluation as a tool to accurately predict lighting, plug loads (office equipment) and catering loads. In the study, detailed sub-metering monitored occupant behavior every half-hour for each of the four tenants in the seven-story building. The overall accuracy of the predicted model using sub-metered data was within 3% of the actual energy consumption (Menezes, Cripps & Buswell 2011). The paper is limited since it does not take into account the interdependencies between the HVAC system, heating and cooling loads and energy losses through the envelope. All these variables increase the level of complexity when predicting energy consumption monthly and annually.

In a similar study real-time simulation analyzed the performance of a whole building. The study monitored a commerical building in real time to compare simulated energy consumption using EnergyPlus to that of actual data. Despite real-time inputs discrepencies were observed pertianing to chiller operation strategies (Pang et al. 2012). This can be attributed to the source code and equations used within the program (Zhu et al. 2013).

Sensitivity Analysis

Elie Azar and Carol Menassa address the impact of occupant behavior on energy performance in a typical office building using nine different occupant behavior parameters (Azar & Menassa 2012). These nine parameters will be of key focus when undertaking a site walkthrough and modeling of the UDUB.

Taking Azar and Menassa's results into consideration it helps to understand which parameters will have the largest effect on energy consumption for case study building located in Toronto. A list of the nine parameters is ranked based on their influence coefficient value based on Toronto climate (Azar & Menassa 2012).

1. Building schedule, 0.8052
2. Occupied hours temperature set points- heating, 0.4529
3. After hours equipment use, 0.4168
4. After hours lighting use, 0.3243
5. After hours active HVAC system, 0.2519
6. Occupied hours temperature set points- cooling, 0.1155
7. Hot water consumption, 0.0668
8. Unoccupied hours temperature set points- heating, 0.317
9. Unoccupied hours temperature set points- cooling, 0.0001

In a research conducted by *Menezes et al.* noted the effects of leaving the computers on after hours resulting in an increase in energy consumption from 90 kWh/m^2 to 155 kWh/m^2 (Menezes et al., 2011). In a similar sensitivity analysis study, the top three factors having the greatest influence on an office building were mechanical ventilation rate during daytime winter, lighting control and infiltration rate during nighttime winter (Heiselberg et al. 2009). With synergy being drawn to a number of studies it is evident that the nine parameters do play a critical role in energy consumption and add relevance and validity to the study performed.

The studies have demonstrated that taking into consideration of occupant behavior, scheduling, set points, and after hour activities can help develop strong design predictions. Implementing the suggestions and practices mentioned will require a detailed site and systems analysis of the UDUB.

Review of simulation tools

eQuest is one of eight approved energy simulation programs approved for energy simulation by Canada Green Building Council (CaGBC). Alternative simulation programs include EE4, DOE-2, EnergyPlus, IES Virtual Environment, Hourly Analysis Program (HAP), TRACE 700 and EnergyPro v5.1.

eQuest is has been built upon the well established DOE-2 simulation engine and is the same tool used by MMM Group during the LEED certification process. Maintaining this continuity will prove valuable when making a direct comparison between the initial LEED submission energy consumption and post-construction energy consumptions.

It is important to understand the limitation of the chosen building energy simulation tool, eQuest, to help access any discrepancy between actual and predicted energy performance. eQuest does lack features and options in the areas such as zone loads, interior surface convection, and solar/day lighting analysis. These limitations are not present in programs such as EnergyPlus and IES-VE (Crawley et al. 2008). Through simple testing and verification such as ASHRAE Standard 140-2007, DOE-2.1E "has the fundamental capabilities and appropriate modeling assumptions for load simulation" (Zhu et al. 2013). In further testing, DOE-2.1E was found to be limited in accurately calculating the heat balance between multiple zones because of its simplification for long-wave radiation exchange and multiple zone solutions. Thus, caution should be given when modeling radiant cooling or heating applications and different operating conditions in adjacent spaces. The effect of this can be observed in higher cooling loads and lower heating loads over an annual basis (Zhu et al. 2013). Awareness of these limitations within the source code of the program will help analyze the output data with better understanding and any discrepancies.

Taking all this into consideration, the UDUB does have radiant infloor heating but it is limited to the main floor perimeter. There are limited adjacent spaces within the building that have varying operating conditions that could cause any large inaccuracies for space heating and cooling. Some of the areas might include mechanical, electrical rooms, elevator shaft and delivery bay.

3 Objective

As part of this case study two questions are going to be answered including:

1. Examine the variation between simulated and real data and be able to explain the cause for the differences. Focus will be on 2012 results, as this year has the most complete data.
2. Compare and analyze the difference between LEED proposed energy consumption and 2012 building energy consumption.

By answering these questions it would be valuable to both the University and the operation and management team ensuring the building is running efficiently. For future reference the University can have a benchmark to follow in future constructions or in evaluating existing buildings on campus with similar functionality. Though a third party company operates the building this data will help track the building on a yearly basis and ensure that it's running optimally.

4 Methodology

eQuest v3.64 will be utilized in creating an accurate model of the case study building based on issue for construction (IFC) package and commissioning reports obtained from the university and MMM Group. In addition, comprehensive data will be collected related but not limited to:

I. Occupancy load
II. Occupancy schedule (class schedule, and networking events on weekends)
III. Lighting schedule
IV. Café operations
V. Plug loads
VI. Mechanical equipment performance (from commissioning reports)
VII. Shading devices (percent closed)

Combining this information together will help in the design of the envelope (R-value), space zones, HVAC systems and schedules for lighting office, class and other events. This process will help reduce any assumption entered into the program and produce an accurate model of the case study building.

To accurately simulate the energy consumption of the building for the time period of January 2011 to April 2013 real weather data will be retrieved from Environment Canada weather station. Six possible weather stations in proximity to the UDUB are considered. Onsite weather data will be collected from the building automation system (BAS) for 3-4 days to help determine the local weather station that best correlates with respect to temperatures and relative humidity the building experienced over the years. Through this process an ".epw" weather file will be created and converted into a ".bin" using eQuest weather conversion software.

Utility bills for gas and hydro from January 2011 to April 2013 will be complied for comparison against simulated energy consumption. It must be noted from August 2010 to November 2, 2011 the natural gas consumption was estimated by Union Gas. This resulted in no measured natural gas consumption per month, due to an initial and final reading spanning more than a year. This will render 2011 natural gas consumption data incomplete and unreliable for comparison with simulated output data.

5 Description of Case study

General

The UDUB is a five story, 9,624 square-meter university building. The facility includes a teaching auditorium, classrooms, offices, amenity spaces and a café on the main floor of the building. Currently only three floors of the building are occupied with the fourth floor remaining incomplete and used as a storage space. The fifth floor contains the mechanical room and other miscellaneous equipment needed to operate the building. The capacity for each floor is as follows; first floor 600 persons; second and third 300 persons each; fourth is not applicable (incomplete); and fifth 11 persons. Refer to Table 1 below for a summary for the major inputs and parameters entered into eQuest during the modeling phase.

Table 2 Input summary table

Input Summary Design Model Characteristics	
General	
Location	Toronto, ON
Simulation Weather File	Custom weather file covering 2011, 2012 and 2013 based on site location and CTMY2 Toronto.bin
Climate Zone	Climate Zone 6
Modeling Software	eQUEST 3.64
Building Area	96,780 ft^2 (Conditioned)
Hours of Operation	Monday to Friday: 6:00 AM to 11:00 PM Saturday: 7:00 AM to 10:00 PM (depending on weekend events and month) Sunday/Holiday: Closed
Envelope Performance	
Overall Roof U-value	Roof Type 1 & Roof Type 2: U-0.187

Input Summary Design Model Characteristics	
(BTU/h·ft²·°F)	
Overall Wall U-value (BTU/h·ft²·°F)	Average: U-0.306
Percentage Glazing	15%
Overall Glass U-value including frame (BTU/h·ft²·°F)	Field House: U-0.36; SHGC-0.40
Internal Loads	
Occupancy	Level 1: 600 Level 2&3: 300 each Level 4: Incomplete Level 5 (mechanical): 11
Lighting Power Density (LPD) (W/ft^2)	As per lighting drawings (space by space method)
Lighting Controls	Occupancy sensors in, classrooms, office, lounge
Exterior Lighting (W)	Total exterior wattage = 7,610 W
Plug-Loads (W/ft^2)	Depending on Room function
DHW Consumption (GPM)	2.1
Mechanical Systems	
Indoor Design Temperature for Conditioned Areas	• Occupied: 70°F heating, 73°F cooling • Unoccupied: 65°F heating, 78°F cooling
Maximum Heating Supply Air Temperature	• Heating: 90°F
Minimum Cooling Supply Air Temperature	• Cooling: 55°F
System Description	**Out door air makeup unit**: Pre conditions the outdoor air to a minimum setpoint, with a built-in economizer and energy recovery wheel. System capacity 16000 CFM, fan power 0.00105 kW/CFM. 100% outdoor air system **Heat pumps units:** Over 100 heat pump units tied into the chilled water loop and hot water loop. **Force Flow heaters & Unit Heaters:** Tied into the hot water loop located in storage areas and vestibules.
Heat Recovery	Enthalpy wheel, effectiveness: 60%
Central Plant	
Heating Type & Hot Water Loop	• Heat Pump and Force flow and unit heaters, natural gas condensing boiler o Capacity: 712 kBTU/h o Efficiency: 90% o Design supply: 180°F o Design loop DT: 40°F • OAMU natural gas condensing boiler o Capacity: 1.44 kBTU/h

Input Summary Design Model Characteristics		
	o Efficiency: 90% o Design supply: 180°F o Design loop DT: 60°F	
Chiller	• Fluid coolers o Capacity: 2820 kBTU/h o Fan power 22.3 kW/ cell, 1 cell o In: 98°F, Out: 88°F	
Domestic Water Heater	• Electric Heater, four each with efficiency of 73%	
Pumps	• Chilled water loop primary pumps (P-01) o Head: 80 ft o Mechanical efficiency: 83% o Variable speed drive • Secondary Heat pump Loop (P-02&03) o Head: 96 ft o Mechanical efficiency: 62% o Variable speed drive • Hot water loop (P-04&05) o Head: 66 ft o Mechanical efficiency: 65% o Variable speed drive	• Heat pump hot water loop primary P-06&07) o Head: 15 ft o Mechanical efficiency: 65% o Variable speed drive • Hot water loop for OAMU (P-08) o Head: 48 ft o Mechanical efficiency: 62%% o Constant speed • DHW Loop o Head: 0.5 ft o Mechanical efficiency: 77% o Variable speed drive

Shell and HVAC

The basic design of the building shell comprises of a curtain wall system for maximum daylight penetration. The interior of the building has a central atrium space that allows daylight to enter deep into the core of the structure. The mechanical system is a hybrid system comprised of a water loop heat pump system in conjunction with an outdoor air makeup unit (OAMU) for fresh air ventilation. The system contains an economizer and energy recovery wheel to help save energy. Smaller systems are also incorporated including radiant floor heating on the first floor along the perimeter and fan coil heaters in designated zones.

Modelling of mechanical systems

The design of the HVAC system in eQuest was modeled based on IFC mechanical engineering drawings. Modeling this information into eQuest is divided into two sections, water-side HVAC and air-side HVAC design.

Water-side HVAC

Three boilers were modeled in total for the system. Boiler one provides hot water for baseboard heaters, unit heaters and fan coil heaters located on the first, fourth and fifth floor. Boiler two ties in with the water loop heat pump for the first, second and third floor. Boiler three supplies hot water to the outdoor air makeup unit (OAMU) to precondition the outdoor air for the whole building. The OAMU is assigned to a dummy zone within the building. It must be noted that the load from boiler three is taken into consideration for total electricity consumption in the building and does not have a value of zero. Four electric hot water tanks located throughout the building supply domestic hot water to washrooms, kitchens and showers.

Air-side HVAC

Heat pumps, unit ventilators, fan coil heaters and/or baseboard heaters supply each of the zones. Fresh air for the building is supplied by the OAMU, which has an actual output of 7931 L/s (16,805 CFM). The OAMU is assigned to a dummy zone within the building since eQuest cannot model multiple HVAC systems for a given zone. The dummy zone has no internal loads such as people, lighting, equipment, exterior surfaces and envelope. The energy consumed by the OAMU supplying the dummy zone will be included in the total electrical and natural gas consumption.

6 Results and Discussion

Based on the modeled information, the output results from eQuest for 2011 to 2013 and CTMY Toronto weather average are presented in the following section. The generated output is divided into two energy consumption sources including electricity (kWh) and natural gas (m^3). Table 2 summarizes these results.

Electrical results

In all four-simulation runs the electrical consumption correlated very closely with actual electrical consumption. The largest performance gap occurs in 2011 with an overall annual difference 6.4% below actual. The 2012 and CTMY weather files generated the most accurate predicted electrical consumption at 0.7% and 0.3% respectively. For the current year 2013 the performance gap is 19.5%; however, the data is incomplete and a clear conclusions cannot be reached. On a monthly cycle, for all four simulations during the months of May/April the largest performance gaps were noted. The largest gap occurs in May of 2011 with a difference of 51.6% below actual.

It can be proven conclusively that eQuest has the ability to accurately simulate annual electrical consumption at a high level of accuracy. This is provided scheduling, mechanical and occupancy loads are accurately simulated. Areas of concern will be draw towards transition months such as May/April where the largest performance gaps are noted. It is not clear if this gap is due to operational inefficiencies and a potential savings or computational based on algorithms within eQuest.

Natural gas results

The predicted natural gas consumption is harder to analyze with certainty due to the lack of accurate data. There are high levels of fluctuation in the results given each year has a varying number of heating degree-days (HDD). 2011 data cannot be used due to the absence of monthly-metered data. Comparing the 2012 and CTMY weather files to 2012 actual data the performance gap ranges from 4.5% below to 15.9% above actual for the respective weather files. The main reason for such a large difference between 2012 and CTMY weather average can be attributed towards the number of HDD contained within the weather file. In 2012 there was approximately 3346 HDD, compared to CTMY Toronto average of 4813 HDD. This can help attribute the difference between 2012 actual natural gas consumption at 34,798 m^3 and CTMY, 40,325 m^3. As noted by the study conducted by Zhu et al. eQuest's results for natural gas consumption where lower than actual, except for the CTMY weather file average. No conclusive result can be drawn with limited data for the accuracy with which eQuest can predict natural gas consumption.

On a monthly cycle, the natural gas consumption in May 2012 predicted consumption is 75.2% above actual and 41% below actual for February in 2013. CTMY Toronto weather file presented a similar difference in April and October with 84.1% and 86% both above 2012 actual, respectively. It is in the transition months specifically May/April and October where the largest differences occur most likely due changing weather conditions.

Natural gas consumption is heavily dependent on the weather file used as it has a direct correlation to HDD. The differences are evident when examining 2012 and CTMY results having a 3-fold difference. Similar to electrical consumption, large fluctuations are noted during spring and fall seasons. With limited data it is not possible to conclude the reason for this discrepancy either being operational inefficiencies or computational. More attention should be given to this area and identifying the sources of error.

LEED comparison

Comparing the 2012 actual utility consumption to that submitted during the LEED submission we can note large discrepancies. Electrical consumption is 30% more and natural gas consumption 27% less when compared to 2012 actual. The reason for such diverging data is because under current conditions the building is at 50% of its occupancy load as compared to 90% for LEED submission. The direct relationship between occupancy load and electrical consumption would help explain this difference. With relation to reduction in natural gas consumption, an increase in occupancy load would correlate to an increase in internal heat gain thus reducing the demand for heating. Other differences to note are different zoning designs, occupancy schedules, lighting densities, temperature setpoints and mechanical systems and efficiencies.

Table 2 Summary of results

Electricity (kWh)	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**TOTAL**	**Delta (%)**
2011 predicted	88792	80035	88196	88839	94938	94423	107970	105076	95175	90237	79638	83798	1097115	6.4%
Actual 2011	96973	78202	85329	71455	62636	96909	105621	96216	86743	83164	81257	86982	1031486	
2012 predicted	87069	78436	89364	88564	97842	96079	107156	104727	93601	89672	79965	83656	1096133	0.7%
Actual 2012	91818	81000	84247	75187	89791	97875	108460	99313	92399	92549	88009	87686	1088332	
2013 predicted	87541	79211	87399	5890	0	0	0	0	0	0	0	0	346392	19.5%
Actual 2013	99686	86100	97769	6331	0	0	0	0	0	0	0	0	289886	
Natural gas (m^3)														
2011 Predicted	8017	6464	5572	3495	1121	71	6	37	300	2349	3840	6101	37370	33%
2011 Actual	12685	10422	9427	5619	2553	456	64	101	1142	4081	2531	6709	55789	
2012 Predicted	6880	5442	3280	3048	546	144	11	59	481	2312	5057	5963	33227	4.5%
2012 Actual	8247	6984	3443	1967	2198	121	11	61	431	1407	3761	6166	34798	
2013 Predicted	7324	6534	6065	0	0	0	0	0	0	0	0	0	23311	21.7%
2013 Actual	10750	11142	7870	0	0	0	0	0	0	0	0	0	29761	

Electricity (kWh)	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**TOTAL**	**Delta (%) to 2012**
Actual 2012	91818	81000	84247	75187	89791	97875	108460	99313	92399	92549	88009	87686	1088332	
CTMY predicted	89520	80555	88440	89003	92941	92579	104410	104444	93367	90463	80698	85438	1091858	0.3%
LEED Predicted	110376	99300	109434	109937	118701	137752	147706	146152	122584	109638	98874	110793	1421247	30.6%
Natural gas (m^3)														
2012 Actual	8247	6984	3443	1967	2198	121	11	61	431	1407	3761	6166	34798	
CTMY Predicted	8066	6684	5615	3628	1115	241	28	54	461	2626	4958	6849	40325	15.9%
LEED Predicted	6699	5312	3294	1214	306	62	14	25	156	928	2306	5037	25354	27.1%

7 Conclusion

Four simulation models were created for the case study building, 2011, 2012, 2013 (January to March) and CTMY 30 year Toronto average. There is still a performance gap being noted on a monthly basis for electrical and natural gas consumption, which should be, addressed in future studies. Based on the results and analysis the following conclusions can be derived:

- eQuest is able to simulate annual electrical consumption to an accuracy under 1%.
- The largest performance gap on a monthly basis usually occurs in May/April and close attention should be given to these months in future simulations.
- A clear conclusion cannot be drawn for natural gas consumption given the limited data. For 2012 natural gas consumption is 4.5% below actual consumption and CTMY 15.9% above actual consumption.
- The largest performance gap on a monthly cycle for natural gas consumption occurs in May, April and October.
- Further analysis should be done during the transition months to determine the cause for the high performance gaps. Is there a potential savings that could occur during these months or is it computational?

Recommendations

When evaluating a building's actual energy consumption versus predicted it is hard to find the root cause of the difference because all possible errors within the program are occurring simultaneously. This includes occupancy load, scheduling, lighting schedule, temperature set points and HVAC design.

In future studies involving the UDUB gathering accurate utility consumption and sub-metered data is of primary importance. In the process accurate end use electrical consumption within the building can be properly verified and cross-referenced with simulation runs and utility bills. This will help to accurately input values for plug loads, office equipment and miscellaneous equipment, which have a direct effect on internal heat gains. It must be noted that there will be an increase in electrical consumption as the occupancy increases.

To help increase the accuracy with which the building is simulated, using onsite weather data would be recommended. By installing a onsite weather station, collecting temperature, relative humidity, solar radiation, wind direction and wind speed will help create the most accurate custom weather file.

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