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Pulling the Levers on Existing Buildings: A Simple Method for Calibrating Hourly Energy Models

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ABSTRACT

Comprehensive building retrofits require an investment grade audit in conjunction with a calibrated hourly energy model. Even with the most thorough audit processes, uncertainty still remains when identifying and modeling building parameters. This uncertainty propagates throughout the final calibrated model and affects the quality of the energy saving estimates.

This paper, geared towards the typical energy analyst, provides a step-by-step process for achieving more reliable results by calibrating an energy model based on actual utility data. This paper presents the following:

- *a list of essential pre-audit activities, including a robust energy audit checklist containing crucial information for accurate energy models;*
- *a process for calibrating an energy model to actual utility data; and,*
- *a summary of statistical methods to evaluate the strength of the calibration.*

This step-by-step process provides a user-friendly reference for energy modelers to create accurately calibrated energy models with minimal time investment.

INTRODUCTION

Despite new codes, design tools, technologies, media momentum and early success stories, the energy use intensity (EUI) of the U.S. commercial building stock has *increased* by about 12% since 1985 (US DOE 2008). According to projections by the Energy Information Administration, approximately 20% of the 80 billion ft^2 of existing commercial space will be retrofit by 2020. This is only slightly less (3.2 billion ft^2) than the entire amount of new square footage that will be added by 2020. Thus, it is impossible to consider the next generation of building energy efficiency without addressing the enormous potential within existing buildings.

Comprehensive building retrofits require an investment grade audit in conjunction with a calibrated hourly energy model. Even with the most thorough audit processes, uncertainty still remains when identifying and modeling building parameters. This uncertainty propagates throughout the final calibrated model and the affects the quality of the energy saving estimates.

As more and more energy analysts are attempting to simulate the performance of existing buildings, a need exists for a widely applicable method for gathering data and calibrating "commodity energy models" for small to medium sized buildings where sub-metered energy use data is not available. This paper provides a step-by-step

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process for calibrating an energy model to a reasonable level based on actual utility data. This paper presents the following:

- *a list of essential pre-audit activities, including a robust energy audit checklist containing crucial information for accurate energy models;*
- *a process for calibrating an energy model to actual utility data; and,*
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PRE AUDIT ACTIVITIES

Certain activities should be completed prior to the energy audit so that no essential information goes unrecorded during the on-site audit. Essential pre-audit activities are described in the following sections.

Utility Bill Analysis

Utility bill information is the most common way to determine building energy use prior to an audit. At least three years of utility bills should be attained to generate a typical profile of energy use and identify anomalous months. First, the data should be time shifted to match standard monthly energy model outputs from the meter read dates. This is accomplished by multiplying weighted daily average energy use by the number of days per month. Second, utility bills should be examined to determine if the building is using energy as expected. Identifying any anomalies allows the audit to serve as a time to answer questions about these inconsistencies, and ensures that the model is calibrated to typical usage patterns. Finally, understanding utility rate structures can help identify measures to reduce costs to the building owner, such as choosing a different rate structure.

Building Drawings

Scaled building drawings and equipment schedules should be gathered prior to an audit. If available, these drawings indicate where key equipment is located and can be used during the audit to make notes of spatially important parameters. From the drawings, building square footage should be determined and used in conjunction with utility bills to determine energy use intensity (EUI). Detailed drawings and sections can be particularly helpful in identifying wall and roof constructions, window areas, and other architectural information. Lastly, if available, a to-scale drawing can be imported from AutoCAD into most building simulation programs.

Develop an Audit Checklist

While the International Performance Measurement and Verification Protocol (IPMVP) (US DOE 2002) and ASHRAE Procedures for Commercial Building Energy Audits (ASHRAE 2004) provide general guidelines for energy audits, they do not highlight the data most necessary for successful calibration of energy models. The checklist contained in Table 1 ensures that parameters with great sensitivity in energy models are covered in the audit.

Table 1. Energy Audit Checklist

Site and Building Information	Notes
Description of site & location	Note orientation, nearby bodies of water, shading, roadways, etc.
Building Type and Age (yrs)	
Total square footage (ft^2)	
Floor to floor height	Note plenum height & number of stories
Owner/leasing structure	
Occupancy and Zoning Information	**Notes**
Occupancy schedule by zone	Weekdays vs. weekends, seasonal changes?
Diagram of thermal zoning	Mark thermostat (Tstat) locations
Occupant density by zone	Note full time employees vs. transient
Thermostat setpoints by zone	Off-hours setback? Programmable?
Other setpoints	e.g. relative humidity setpoints
Building Envelope	**Notes**
Wall/Roof/Ceiling R values	Need IR camera or thermostat
Window U-value	Note if this includes framing
SHGC and visual transmittance	
Window area (ft^2) per facade	Note any shading devices
Note infiltration controls	e.g. weather-stripping at doorways
Blower door test results	
Wall and roof solar reflectance	
Lighting	**Notes**
Interior and exterior lighting inventory	Note lamp & ballast types, wattage and quantities
Illuminance and luminance measurements by zone	
Lighting power density (LPD)	
Description of interior and exterior lighting controls	Note location of occupancy sensors
Description of daylight access	Evaluate potential for daylight
Surface reflectance values	
Miscellaneous Equipment	**Notes**
Description of misc. loads	Plug/process loads, appliances, etc.
Equipment power density (EPD)	Useful to have watt-meter
Description of controls	
HVAC Equipment	**Notes**
Description/Type	Note server rooms & associated systems
Age (yrs)	
Capacity (Btu/hr, cfm)	
Operation schedules	
Efficiency	
Rated fan power	Note motor efficiency & fan operation
Fraction of outside air (OA)	Note OA controls (e.g. economizer, demand control ventilation, etc)
Supply air temp (°F)	Reset schedules?
Equipment model numbers	
Domestic hot water information	Efficiency, insulation, tank size, etc.
Control and Maintenance	**Notes**
Building automated controls?	Obtain points list & control sequences
Maintenance and operating logs	Schedules and contractor contact info

Weather Analysis

When calibrating an energy model, it's essential to use a custom weather file that contains historical weather data for the years that correspond to available utility data. Begin with a Typical Meteorological Year (TMY) file and convert this to Microsoft Excel format for customization. Obtain as much hourly weather data as you can for the time period of interest and replace the TMY hourly values with the real time data. In some cases the only data that will be available are temperatures. Sources that prove useful in this process include:

1. The EnergyPlus website (EnergyPlus 2009) maintained by the US Department of Energy; good source for TMY files and real time data requests
2. The U.S. Department of Energy – Energy Efficiency and Renewable Energy website (US DOE EERE 2009)

Benchmark Data

The Energy Information Administration (EIA) maintains a database of energy consumption for commercial buildings called CBECs (Commercial Building Energy Consumption Survey) (US EIA 2009). This database provides benchmark data for existing buildings, including typical energy end use breakdowns and EUIs. Prior to any energy audit, this data should be analyzed for the relevant building type and climate zone and compared to actual utility data. Typical CBECs end use break downs should be determined and used as a sanity check when calibrating the energy model.

Create Building Occupant Surveys and Interview Questions

An occupant survey should be developed to elicit feedback regarding indoor air quality, thermal comfort, acoustical and visual quality, and general building satisfaction. Sample surveys are available from institutions such as the Center for the Built Environment (University of California 2009), but all surveys should be tailored to a particular building. Survey results can be pivotal for influencing the implementation of measures (e.g. a result showing that 70% of employees are dissatisfied with a lack of daylight could influence the owner to implement a daylighting measure with a high capital cost).

CALIBRATING BUILDING ENERGY MODELS

In calibrating a building energy model, a comparison of modeled and measured energy use values is used to create a model that represents actual building performance. Frequently, the only measured data will be from utility bills, although sub-metered data may be available from the audit or the building operator. Model calibration is an iterative process that involves evaluating information about the building collected during the audit, and adjusting the values of questionable model inputs. It is important to remember that building energy models are under-determined problems; many different combinations of model inputs may produce the same annual energy use and professional judgment guides many decisions.

A variety of techniques have been published to describe appropriate calibration methods and sequences. The IPMVP and Westphal and Lambert (2005) provide methods to calibrate models where hourly data is available with Westphal and Lambert including the use of sensitivity analysis of building parameters. Yoon et al. (2003) provides an excellent flow chart to guide the calibration process. The reader is also directed to ASHRAE Guideline 14 Section 6.3 (ASHRAE 2003) for a thorough discussion and list of references on this topic.

The procedure summarized in Figure 1 serves to guide the calibration process. While the procedure is general, to provide a widely applicable guideline, building characteristics and climate must be considered when customizing this procedure to any project. The term parameter is used to describe any input to the model.

Figure 1: Process for Building Model Calibration

Identify and Classify Known and Unknown Model Parameters

The quality of a building model is dependent upon the quality of the inputs to that model. The recommended pre-audit activities should provide as many accurate model parameters as possible. Despite these best efforts, there will be some data that is inaccurate or missing.

The calibration process should begin, before the model is even created, with an organized list of parameters and an assessment of the certainty of each parameter. Parameters should be classified according to those that were firmly established in the audit, those that may be partially understood, and those that are completely unknown. This list of parameters will serve as the foundation for the remainder of the calibration process, which will attempt to determine appropriate values for unknowns, and discover any idiosyncrasies that may have been missed in the audit.

Estimate Values for Unknown Parameters and Create Feasible Ranges

Once the certainty of the model parameters is established, a range of probable values must be determined for the parameters that are not well known. In many cases, unknown parameters can be determined using information gathered during the audit. For example, any available nameplate information may lead to manufacturer data sheets. Contacts with a maintenance contract company, or even equipment depreciation schedules, may provide clues to equipment properties. Sometimes, there will simply be parameters that are not well understood. In these cases, existing studies should be consulted to determine typical values. For example, typical plug and lighting loads for various building types can be found in the ASHRAE Handbook of Fundamentals (ASHRAE 2005). Many building and mechanical system properties can also be estimated by consulting local codes or federal baselines for the time period in which the building was constructed or the equipment was added.

Create and Analyze Initial Model

After the initial list of model parameters and values is established, a baseline model should be created that contains all known parameters and the expected values for the unknown parameters. At this time the model's performance should be checked against the benchmark data developed prior to the audit, as well as any measured data, and general expectations from the audit. Investigating thermal comfort, equipment part load operation and other outputs can provide valuable insight to model performance. It is encouraged to "gut check" model outputs by asking questions such as "Why does this model use much less energy than similar buildings in CBECS? If we know this building is often under-cooled, then why does initial model show that the setpoint is maintained for all hours of the year?" This step will provide an opportunity to catch major errors in the energy model and will start to give clues about which parameters are most important.

Calibrate Model to Address Individual Loads

Once the initial model is producing reasonable results, many parameters affecting individual loads can be calibrated against known or estimated energy consumption. Examples of individual loads may include domestic hot water (DHW) use and individual pieces of equipment such as refrigerators or air compressors. In conducting this calibration phase, the only model output of interest will be the energy use of the individual load in question. Any sub-metered loads should be calibrated by adjusting equipment properties and schedules.

One way to calibrate parameters related to an individual load is to find a period of time in which the load in question is the only load on the meter. The most common example is that in many cases DHW energy use is the only natural gas load during the summer. Hot water use and hot water equipment performance can be estimated for the entire year based on gas use during the non-heating months.

Many appliances, or miscellaneous equipment, can be calibrated against expected annual energy consumption values, such as values available from the EERE or Energy Star (US EPA 2009). In these cases, the component in question, such as refrigerators, may be individually calibrated by using default annual usage schedules and iterating the peak power draw until the expected annual electricity consumption is produced. In the cases where sub-metered data are available a similar procedure may be followed. For example, a load for an air compressor could be calibrated by adjusting the schedule and peak power draw to match measured data. In some cases sub-metered data will be available for HVAC equipment whose energy use is affected by other loads. In these cases the sub-metered data should be used in conjunction with the process described in the next section.

Calibrate Remaining Parameters

The final step in calibrating the energy model is to use an evaluation of modeled and measured energy use to adjust any remaining uncertain parameters, including those parameters related to HVAC equipment that is affected by other loads. A general process is described below, but may be adapted depending on the properties of the building and climate.

Modeled energy use should first be evaluated during the swing seasons (fall and spring) as these are usually time periods where the only energy use will be associated with internal energy use and ventilation. Heating will be minimal and cooling energy will be associated with internal loads, not climate. During this time period, internal loads, fan power, and schedules can be calibrated. Parameters that have already been set in previous steps should not be adjusted further. Common errors with fan power are often associated with the amount of outside air brought into the space and whether fans run on a continuous or intermittent basis.

Once the baseline gas and electric loads are established, the HVAC system can be calibrated during the heating and cooling season. This may require small adjustments to building shell parameters that are not entirely certain. The building shell can be calibrated along with heating equipment properties and setpoints during the winter months and the cooling equipment efficiencies and setpoints can be calibrated during the summer months. It is important to check fan use and settings during the heating and cooling season to ensure that this equipment is modeled properly. This can become an iterative process if there are many uncertain parameters. It may be necessary to complete several iterations, adjusting individual parameters until the model performs well.

At the end of this process, the model outputs should compare well against measured data and the model is considered calibrated. If the statistical requirements mentioned in the next section are not met, the process should be reevaluated and repeated. Focus should be given to those parameters that have the greatest uncertainty. Considerable judgment should be exercised to ensure that the final model matches the idiosyncrasies of the building in question.

Comparing the Model Output and Measured Data

Throughout the calibration process, model output data will be compared to measured data. Statistical or graphical measures can aid in this comparison. In most cases, the only available data on building performance will be monthly utility bills along with any data gathered during the audit process. This section is directed to the practitioner using monthly utility data, but data at a finer resolution should be used, if available.

When calibrating a model to monthly data, the user should use as many measured data points as possible, including use and demand values for gas and electric energy. Monthly utility data can be compared to model outputs using statistical and graphical techniques. Plotting measured and predicted (modeled) monthly data values on the same chart allows for easy identification of those months that have the largest mismatch between predicted and measured values. This may allow the practitioner to identify likely sources of error and aid in calibrating the model.

It is important to use statistical methods to quantify the error that exists between the predicted and measured energy use. These methods allow for a concise explanation of model fit as well as providing a metric to determine calibration accuracy. ASHRAE Guideline 14 recommends the use of the coefficient of variation of the root mean square error (CVRMSE) and the normalized mean bias error (NMBE), which are shown in Equations 1 and 2 respectively. The NMBE describes the variation between the mean measured and predicted values while the CVRMSE describes the variation in the pattern of the data. Guideline 14 recommends that a calibrated model will have a NMBE of ± 5% and a CVRMSE of ±15% when using monthly data.

$$CVRMSE = 100 * \frac{\sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-1}}}{\bar{y}} \quad (1)$$

$$NMBE = 100 * \frac{\sum(y_i - \hat{y}_i)}{(n-p) * \bar{y}} \quad (2)$$

y = measured value
$\hat{y}$ = model predicted value
$\bar{y}$ = mean value of the measured data
n = number of samples
p = P-value; for this purpose p = 1

For example, if one were to compare monthly energy use data for a building, i would represent each individual month. Therefore, y_{jan} would be the utility energy use for January, $\hat{y}_{jan}$ would be the modeled energy use for January, and $\bar{y}$ would be the average utility energy use for the entire year.

If an electricity bill contained the monthly energy use (kWh) and demand (kW), then two points of comparison are available. Further points could be gathered from a gas bill. For hourly comparisons a NMBE of ± 10% and a CVRMSE of ±30% is appropriate for a calibrated model.

CONCLUSION

Following a clear procedure for calibrating energy models can reduce the time and effort required to accurately assess building energy retrofits. Certain pre-audit activities are equally important, and greatly improve the quality of data from which energy models are calibrated.

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