Streamlining Energy Simulation To Identify Building Retrofits

By **Aleka Pappas, P.E.,** Member ASHRAE; and **Sue Reilly, P.E.,** Member ASHRAE

For existing building energy retrofits, developing a streamlined and cost-effective energy modeling process is critical. The process should provide building owners with accurate and timely information at a reasonable cost to allow them to make informed decisions about implementing energy efficiency improvements. Usually, only limited resources are available for investing in energy efficiency, so it is important to rank alternatives in terms of return-on-investment to build the case for immediate and future investments in efficiency.

Our firm was recently tasked with carrying out energy audit assessments for three General Services Administration (GSA) Region 3 buildings, with the work funded through the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), and driven by Executive Order 13423, "Strengthening Federal Environmental, Energy, and Transportation Management," part of the Energy Policy Act of 2005, and the Energy Independence and Security Act of 2007. For each building, we partnered with NREL to carry out a walk-through audit assessment. We developed a calibrated building energy model that was used to calculate annual energy cost savings for a number of energy efficiency measures (EEMs) and provided a life-cycle cost analysis for each measure. Finally, the audit assessment process, results of the analysis, and recommendations were summarized in detailed reports that provided key decision-makers with the information they needed to move forward with implementation.

In this case study, we focus on one of the three buildings: the Fallon Federal Building in Baltimore (*Table 1*). We present a relatively quick energy audit assessment and model calibration process that resulted in investment grade calculations for a number of EEMs. The process includes calibrating a whole building annual energy model to monthly utility bills with no submetered energy use or hourly trend data available. The calibrated model was then used to

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Initial Energy Efficiency Measures for GSA Retrofit Project

- Use existing equipment for waterside economizing
- Reenable on-site CHW plant
- Turn down the heating temperature setpoint in the garage
- Replace perimeter FCUs with fewer larger units
- Intermittent control for perimeter FCUs
- Retrofit FCU fan motors with ECMs
- Bring OA rates down to Standard 62.1-2004; use extra capacity for economizer
- Demand-controlled ventilation where not already implemented
- On-site boiler plant
- Put two fans on the BAS to enable unoccupied shut-down
- Enable existing exhaust run-around loop energy recovery
- Optimize the reset schedule on DOA units
- Upgrade to enthalpy heat recovery wheel
- Static pressure reset control in AHUs
- Lower VAV box minimum airflow rates to reflect cooling loads
- Install lighting controls at the circuit level in section of building
- De-lamp some HIDs in the garage
- Daylighting controls in lobby
- Daylighting controls in perimeter offices
- Low-flow water fixtures
- Software to manage computer runtime hours at night
- Photovoltaic system

Location	Baltimore, ASHRAE Climate Zone 4A
Building Parameters	735,300 ft^2 Includes 17 Above-Grade Stories and a 1.5 Story Below-Grade Parking Garage; Late 1960s Construction
Space Use	Mainly Office Space for Government Agencies
Occupancy	1,200 People
HVAC System	Multiple VAV AHUs on Lower Three Levels, Two-Pipe FCUs at the Perimeter Zones in the Upper Levels, Dedicated Outside Air AHUs Provide Ventilation to the Entire Building
Lighting System	Mainly 4 ft T8 lamps with Electronic Ballasts
Chilled Water Source	Purchased at About $0.30/ton·hr (2009) (Disabled On-Site Chilled Water Plant)
Hot Water Source	Purchased Steam at About $21.50/thousand lbs (2009)
Cost of Electricity	$0.121/kWh Blended Rate (2009)

Table 1: Fallon Federal Building overview.

calculate annual energy cost savings for the EEMs.

This case study gives an overview of our approach, highlighting strategies used to streamline and reduce analysis time. For some analysis details, the degree of accuracy is reduced in favor of analysis speed; a sensitivity analysis showed that this did not significantly impact final results and recommendations.

Analysis Process

Our premise is that the cost of the audit assessment and analysis should be considered relative to the total life-cycle value of EEMs. For a typical audit assessment, the cost of the analysis should not significantly increase the simple payback period or life-cycle net present value of recommended EEMs. For this project, the entire analysis and reporting process took just under 300 hours of work, and our consulting fees increased the calculated life-cycle value of recommended EEMs by 0.7%. This time could be further reduced through streamlined reporting. The International Performance Measurement and Verification Protocol (IPMVP[2]) discusses the idea of balancing uncertainty with analysis cost. The Fallon Federal Building is large and has high costs of purchased steam and chilled water, so relative analysis costs were low.

We focused on increasing energy modeling speed when selecting a modeling tool and developing the process. DOE-2.2 with the eQuest interface was selected as the most appropriate modeling tool. The ultimate goal of the modeling was to determine annual energy cost savings to calculate payback periods and life-cycle net present values for EEMs. Realizing that 10% to 20% error in energy modeling results is acceptable based on this goal allowed for a quicker and less detailed energy modeling process; a sensitivity analysis described below backs up this approach. Early in the analysis, we identified the model inputs necessary to ensure greater levels of accuracy, which then allowed for focused efforts and reduced time spent collecting information.

Data Collection

The data collection process consisted of three stages: 1) collecting information before the site visit, 2) on-site information gathering, and 3) compiling and processing information into model inputs.

Before the site visit, we requested three years of utility bills from the building, as-built MEP drawings, and asked about the possibility of starting trends at the building automation system (BAS) that we could later collect when on site. We were not able to obtain BAS trend data or building plans before the site visit. Involving the building staff throughout the energy audit process allowed us to gather information more quickly, and gave us invaluable insight about how the building was working and could be working. It made the process more transparent, and implementation of EEMs became more likely with initial buy-in from building staff. We planned each day of the site visit and ensured that building staff had time scheduled to help. We also had a controls expert on site to help with functional testing and obtaining data from the BAS.

Initial EEM List

Developing an inclusive, but refined, list of EEMs to analyze may have been the most critical part of this process (see sidebar, Initial Energy Efficiency Measures for GSA Retrofit Project). We developed this list while still on site; this allowed us to take advantage of insight from the building staff, and get their responses to the list before we started modeling. The list served as a driver for the analysis and was refined throughout the process; it helped us determine critical model inputs and gave insight to the most appropriate model calibration approach.

Using a whole building energy simulation tool with the capability of running multiple parametrics in a short period of time allowed us to work with a fairly exhaustive list of EEMs. Although we eliminated measures that were not feasible, we did include any EEM that we or the building staff thought was worth pursuing.

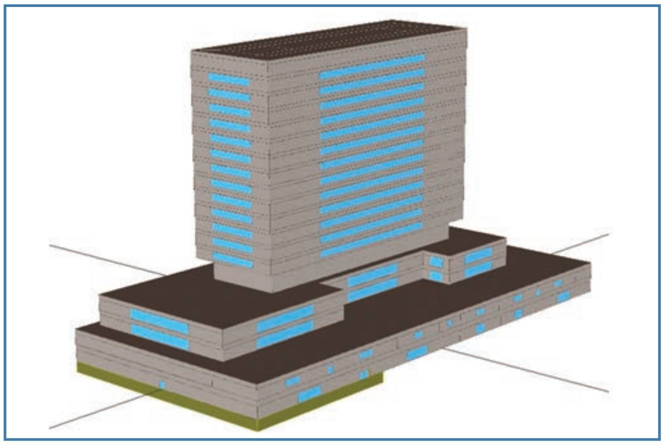

Figure 1: Sketch of energy model geometry.

Model Development and Calibration

The calibration target for the energy model from NREL was to achieve within 10% of annual building energy cost. This is a fairly course calibration target, with thousands of different combinations of model inputs as possible solutions. We used experience, observation, and existing research to determine which inputs to vary for calibration while trying not to spend time on details that would not impact results. We first separated the list of model inputs into three categories: known values, roughly known values, and unknown values (*Table 2*).

We started developing the model by incorporating all of the known and roughly known values, and inputting mid-range values for the unknowns. We incorporated simplifications whenever possible that would not significantly impact results for the list of EEMs.

The building geometry and zoning was greatly simplified, resulting in a significant reduction in modeling time. We took care to model the exterior wall, roof, and window areas accurately per orientation, but grouped together surfaces whenever possible. Zoning was detailed enough to assign appropri-

Known Values	Source	Approach
HVAC Equipment Capacities, Efficiencies	As-Built Drawings, Verified On Site	Acceptable level of accuracy achieved with collected information. These values were fixed during model calibration.
HVAC Operating Schedules	BAS, Conversations with Staff	
HW, CHW, AHU Setpoints	BAS, Conversations with Staff	
Fan and Pump Peak kW	Calculated From amp Readings and Nameplates	
HVAC Functional Conditions	BAS, On-Site Functional Testing	
Lighting Power Densities	As-Built Drawings, Verified On Site	
Lighting Controls	Conversations with Staff, Verified On Site	
Building Geometry	Construction Documents, Verified On Site	
Window Geometry and Performance	Cut Sheets, Verified On Site	
Cost of CHW, Steam, and Electricity	Contracts with Utilities and Utility Bills	
Roughly Known Values	**Source**	**Approach**
Ventilation Airflow Rates	BAS (Damper Positions) and MEP Schedules	Fixed Based on Best Estimate
Wall and Roof R-Values	As-Built Drawings, Unverified	Fixed (Minor Impact on Results)
Data Center Airflow Rates	CRAC Equipment Capacities, Site Observations	Fixed Based on Best Estimate
Elevator Energy Use	Typical Values From Published Research	Fixed (Minor Energy Use)
Weather	TMY2 File for Baltimore	See Sensitivity Analysis (*Table 5*)
Unknown Values	**Source for Range**	**Approach**
Plug Load Power and Schedules	Experience, Occupant Density, and Publications	Used for Electricity Calibration
Kitchen Energy Use	Typical Values and Conversations with Staff	Fixed (Minor Energy Use)
Building Infiltration	Typical Values for Similar Buildings	Used for CHW Calibration
Parking Garage Infiltration	Typical Values and Observations	Used as a Single Variable for Steam Calibration
Steam Valve Leakage	Estimated Based on Observations	

Table 2: Summary of model inputs.

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ate floor area to each AHU, or group of FCUs with the same orientation, which led to a fairly basic perimeter/core zoning pattern. The total modeling time spent on the building geometry was about three hours.

Of equal importance, the model runtime on a 64-bit desktop computer with an Intel Core2 Quad processor was around 16 seconds; this allowed us to run the model repeatedly as required for error checking throughout the development process. Our comfort level with these geometry simplifications stemmed in part from knowing that building envelope upgrades would not fall within acceptable economic criteria for this project; our focus was on lighting and HVAC measures.

Another simplification was in using a TMY weather file during calibration instead of actual weather data. Resulting errors would be cancelled out during the calibration process, and by taking the difference of results from two models (baseline model energy cost minus EEM model energy cost) to calculate annual energy cost savings. As a check on this assumption, we ran the models with a weather file from Atlanta, which has 36% fewer heating degree-days and 36% more cooling degree-days than Baltimore. Without going through a calibration process with this weather file, annual energy cost savings for our final bundle of recommended EEMs changed by 16%. As shown in the sensitivity analysis summarized below, this variance in annual energy cost savings would change the payback period calculation for the bundle of EEMs by less than one year. Furthermore, if the models had been calibrated to this new weather file, we expect the change in results to be lower.

After the initial model development, the model was thoroughly checked for errors until the simulations seemed to be giving realistic results. When deciding how to calibrate this model, we considered: 1) only the unknown and roughly known values can be varied for model calibration; and 2) energy cost savings calculations for EEMs should not be strongly, if at all, dependent on values varied for calibration. We also kept in mind that energy modeling is a process that requires well thought out simplifications of the actual building; the more justified simplifications you can make, the more usable and comprehensible the model becomes, while still maintaining the desired level of accuracy. This leads to a process in which more time is spent in planning the analysis, and less time spent modeling.

Because this building uses purchased steam for all heating loads and purchased chilled water for all cooling loads, these end-uses were effectively submetered. So, the steam (*Figure 2*), chilled water (*Figure 3*), and electricity energy (*Figure 4*) uses were calibrated independently; this removed a good deal

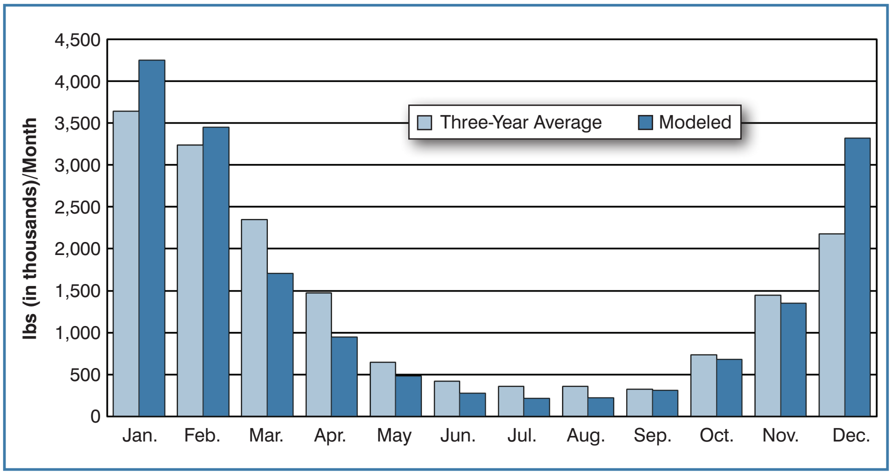

Figure 2: Steam calibrated model and metered use.

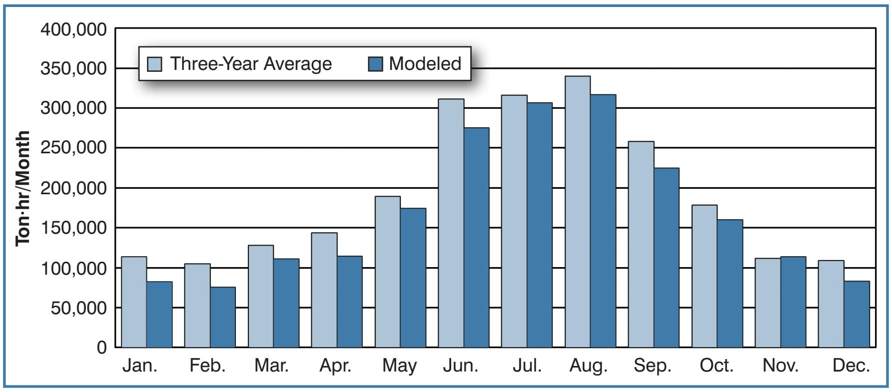

Figure 3: Chilled water calibrated model and metered use.

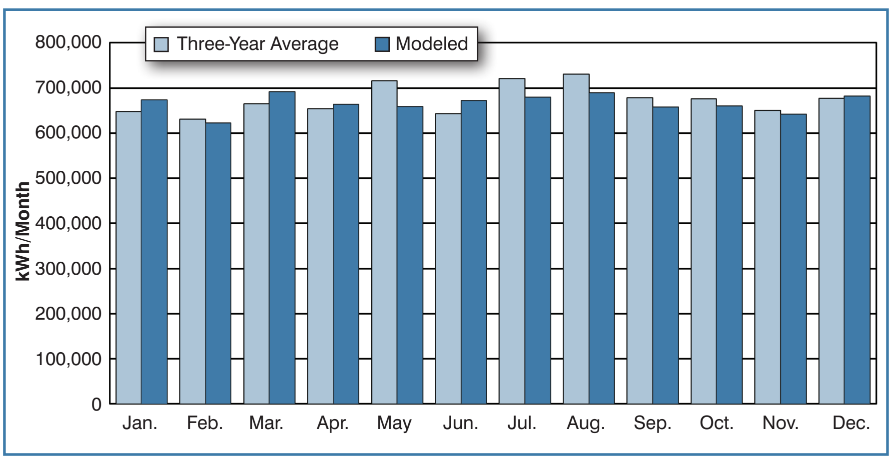

Figure 4: Electricity calibrated model and metered use.

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of variability from the process. We arrived at a single most-rational calibration variable for each of these three energy end-uses.

As shown in *Table 3*, the calibrated model *total energy costs* comply with ASHRAE Guideline 14[1] requirements for monthly normalized mean biased error (NMBE) and for coefficient of variation of the root mean squared error (CV RMSE). The steam energy use does not comply with these requirements. The NMBE is 0% for steam because positive and negative errors are cancelled out; these errors are better represented by the CV RMSE, at 33%. By another metric suggested in the IPMVP[2], the predicted savings should be larger than twice the standard error. Our predicted savings were about 100 times the standard error. The 10% NREL annual energy cost error requirement was met, which was the stated goal for this analysis.

		Annual Error	Monthly Normalized Mean Biased Error	Coefficient of Variation Of the Root Mean Squared Error
ASHRAE Guideline 14		–	±5%	15%
NREL Requirements		±10%	–	–
Calibrated Model	Electricity	–1%	–1%	4%
	Steam	0%	0%	33%
	Chilled Water	–12%	–13%	13%
	Energy Costs	–5%	–5%	12%

Table 3: Model calibration errors.

The major unknown variables affecting steam energy use were parking garage infiltration and leakage in the steam valves serving the garage AHUs, which we knew had been significant and rather sporadic during the periods for which we had utility data. These valves had been repaired just before we arrived to do the assessment. The modeled steam energy use was calibrated by varying the garage infiltration, with a fixed valve leakage value. This approach had the same result as if we had varied both inputs. This was the most difficult energy use to calibrate; the ground level parking garage peak infiltration rate was increased from our initial assumption of 0.007 cfm/ft^2 to 0.020 cfm/ft^2 (0.003 L/s·m^2 to 0.009 L/s·m^2) (where ft^2 is the parking garage floor area) to calibrate the steam energy use.

The modeled chilled water use was very close to measured data before calibration, and was calibrated by slightly changing the building infiltration rate. The building had no air-side or water-side economizing capabilities, so there was a significant chilled water load year-round.

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Annual Electricity Savings (kWh/yr)	Annual Chilled Water Savings (MMBtu/yr)	Annual Steam Savings (MMBtu/yr)	Annual Energy Cost Savings ($/yr)	Annual O&M Cost ($/yr)	Total Annual Savings ($/yr)	Implementation Cost	Simple Payback Period (yrs)	15-Year Life-Cycle NPV*
1,934,516	9,015	1,116	$679,830	$45,986	$633,844	$2,419,582	3.8	$4,983,059

*A nominal discount rate of 4.2%, and an energy cost escalation rate of 0.81% were used for the LC NPV calculations[5,7]

Table 4: Bundle of recommended EEMs.

We obtained a fairly high level of accuracy in the key HVAC and lighting inputs before starting the model; this was a major area of analysis time spent. We calculated peak fan and pump kW, and airflow and ventilation airflow rates as accurately as possible. Functional testing performed during the site visit ensured us of current operating conditions such as valve operating conditions and VFD functionality. Since most of the significant EEMs dealt with the HVAC system, we knew that reaching a high level of accuracy in these model details was most important. For the lighting system details, we used plans of recent lighting renovations and verified the actual lighting systems while on site.

We chose not to spend time pursuing a high level of accuracy in determining plug loads because EEMs would not be focused on this energy use. We did propose one EEM dealing with plug loads (unoccupied hours computer management software), but we focused efforts on HVAC and lighting measures. The plug load power density would not significantly impact energy savings calculations for any of the other EEMs being considered, so this was the obvious calibration variable. We used a W/ft^2 value that was at the high end of a range of values cited in an *ASHRAE Journal* article[4] as a starting point for this input; the occupant density in the building was fairly high, and a quick visual assessment found a large amount of equipment such as personal printers, mini-refrigerators, fans, etc. A typical office building plug load schedule was used, adjusted for the known building schedule.

After the model calibration process, current utility rates were entered, and each EEM was set up as a parametric run in the model, run cumulatively to consider synergistic effects. The list of EEMs was refined and we ended up analyzing 22 different measures.

Economic Calculations

The key economic metrics calculated for each EEM were simple payback period and 15-year life-cycle net present value

Key Variable	Change In Key Variable	Nominal Discount Rate	Energy Cost Escalation	Annual Energy Cost Savings ($/yr)	Annual O&M Cost ($/yr)	Implementation Cost	Simple Payback Period (yrs)	15-Year Life-Cycle NPV	Life-Cycle NPV Percent Change
Baseline		**4.20%**	**0.81%**	**$679,800**	**$46,000**	**$2,419,600**	**3.8**	**$4,982,500**	**–**
Annual Energy Cost Savings	–10%	4.20%	0.81%	$611,820	$46,000	$2,419,600	4.3	$4,191,900	–16%
	–20%	4.20%	0.81%	$543,840	$46,000	$2,419,600	4.9	$3,401,200	–32%
	–30%	4.20%	0.81%	$475,860	$46,000	$2,419,600	5.6	$2,610,600	–48%
	–40%	4.20%	0.81%	$407,880	$46,000	$2,419,600	6.7	$1,819,900	–63%
	–50%	4.20%	0.81%	$339,900	$46,000	$2,419,600	8.2	$1,029,300	–79%
O&M Costs	10%	4.20%	0.81%	$679,800	$50,600	$2,419,600	3.8	$4,932,100	–1%
	20%	4.20%	0.81%	$679,800	$55,200	$2,419,600	3.9	$4,881,700	–2%
	30%	4.20%	0.81%	$679,800	$59,800	$2,419,600	3.9	$4,831,200	–3%
	40%	4.20%	0.81%	$679,800	$64,400	$2,419,600	3.9	$4,780,800	–4%
	50%	4.20%	0.81%	$679,800	$69,000	$2,419,600	4.0	$4,730,400	–5%
Implementation Costs	10%	4.20%	0.81%	$679,800	$46,000	$2,661,560	4.2	$4,740,600	–5%
	20%	4.20%	0.81%	$679,800	$46,000	$2,903,520	4.6	$4,498,600	–10%
	30%	4.20%	0.81%	$679,800	$46,000	$3,145,480	5.0	$4,256,700	–15%
	40%	4.20%	0.81%	$679,800	$46,000	$3,387,440	5.3	$4,014,700	–19%
	50%	4.20%	0.81%	$679,800	$46,000	$3,629,400	5.7	$3,772,700	–24%
Nominal Discount Rate	10%	4.62%	0.81%	$679,800	$46,000	$2,419,600	3.8	$4,766,700	–4%
	20%	5.04%	0.81%	$679,800	$46,000	$2,419,600	3.8	$4,560,000	–8%
	30%	5.46%	0.81%	$679,800	$46,000	$2,419,600	3.8	$4,362,000	–12%
	40%	5.88%	0.81%	$679,800	$46,000	$2,419,600	3.8	$4,172,300	–16%
	50%	6.30%	0.81%	$679,800	$46,000	$2,419,600	3.8	$3,990,400	–20%
Energy Cost Escalation	–10%	4.20%	0.73%	$679,800	$46,000	$2,419,600	3.8	$4,935,800	–1%
	–20%	4.20%	0.65%	$679,800	$46,000	$2,419,600	3.8	$4,889,400	–2%
	–30%	4.20%	0.57%	$679,800	$46,000	$2,419,600	3.8	$4,843,300	–3%
	–40%	4.20%	0.49%	$679,800	$46,000	$2,419,600	3.8	$4,797,500	–4%
	–50%	4.20%	0.41%	$679,800	$46,000	$2,419,600	3.8	$4,752,100	–5%
	–100%	4.20%	0.00%	$679,800	$46,000	$2,419,600	3.8	$4,529,700	–9%

Table 5: EEM Bundle life-cycle net present value sensitivity analysis.

(LC NPV). The simple payback period was the primary metric used to vet the feasibility of EEMs; the GSA is interested in considering EEMs with payback periods of 10 years or less. Nineteen EEMs met this criterion; these were selected to be included in a final recommended bundle of measures. Results for this bundle are shown in *Table 4* (Page 40). The use of building energy modeling allowed us to quickly analyze synergistic effects of all of the EEMs together. Implementation costs were estimated using a combination of RSMeans data[6] and experience. A 30% contingency was added to all estimated costs.

As shown, if implemented all together, these 19 EEMs are predicted to have a simple payback period of 3.8 years, and a 15-year life-cycle net present value of almost $5 million. The bundle is predicted to reduce the annual energy cost by 36% based on the calibrated model. Only five of the EEMs we included in our initial list were not included in the recommended bundle; the effort spent upfront in developing this list paid off in efficiency of analysis.

We performed a rough sensitivity analysis similar to that discussed in the NIST Handbook 1353[3] to see the impact of error in any of our key assumptions on these results. The critical values entering into these economic calculations include:

- Nominal discount rate (adjusted for inflation);
- Energy cost escalation rate;
- Annual energy cost savings (from energy model);
- Annual O&M costs; and
- Implementation cost.

We varied each of these five values by a range of percentages to determine the impact on payback period and life-cycle net present value calculations. The results of this analysis are detailed in *Table 5*. As shown, the greatest impact on results comes from varying in the annual energy cost savings. Decreasing this value by 50%, however, only increased the simple payback period by 4.4 years, which still left the final value within the feasibility criteria of 10 years or less. We expect that the actual error in modeled energy cost savings is significantly less than 50%.

Conclusions

It is important to streamline a process for calibrating energy models for energy audit calculations to make the cost of analysis reasonable for a project, while still maintaining a desired level of accuracy. Modeling accuracy can be sacrificed while still obtaining sufficient accuracy in economic metrics for decision makers. Time-saving strategies that we incorporated into this process include:

- Plan the site visit and open communication paths with building staff to minimize time required later to gather additional information.
- Develop a comprehensive list of EEMs while on site, with input from the building staff.
- Select a modeling tool with the potential for quick implementation and runtime so that calibration can be accomplished interactively.
- When collecting model input data, realize which inputs are less critical and minimize time in obtaining accuracy in these values. Refer back to the initial list of EEMs for insight on what is appropriate.
- Simplify the energy model wherever reasonable; consider implications on time spent collecting model inputs and model runtime when adding detail. Refer to the list of EEMs for insight on what simplifications are appropriate.
- Using a TMY weather file when calibrating the model is likely a reasonable approach if a data file with actual weather is not readily available. Because savings are estimated between a baseline model and the EEM using the same weather data, error in a weather file is somewhat neutralized.

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