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BUILDING ENERGY
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REPORT

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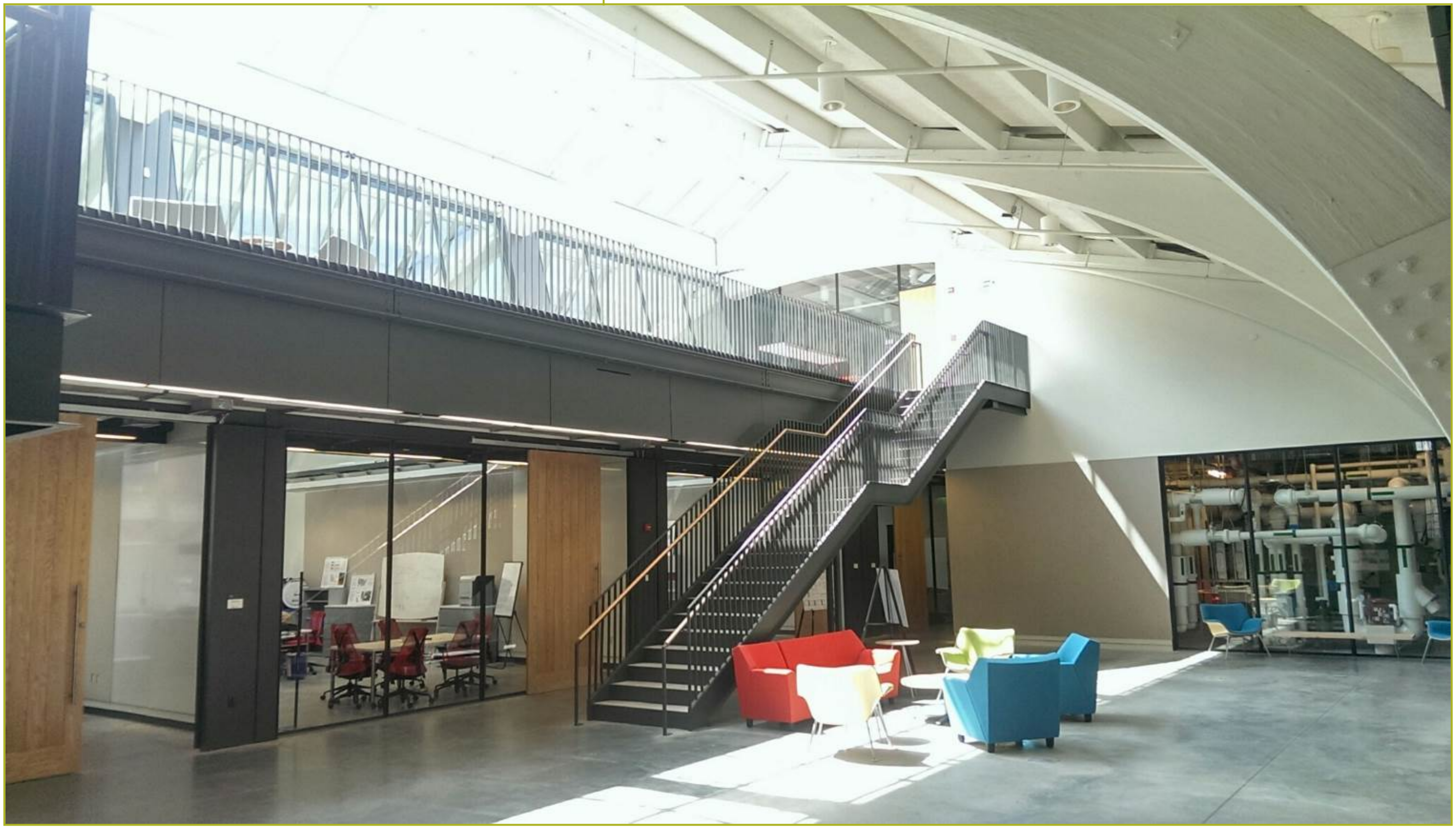

CBEI was referred to as the Energy Efficiency Buildings HUB at the time this report was developed.

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Report Abstract

This report presents an overview of the development of the Energy Audit Tool along with case study results from the analysis of 40 buildings, and nine audited buildings at the Philadelphia Navy Yard.

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Disclaimer

Year 2
Final
Report

2013

This report presents an overview of the development of the Energy Audit Tool along with case study results from the analysis of 40 buildings, and nine audited buildings at the Philadelphia Navy Yard.

Energy Audit Tool

This report was developed by the Energy Efficient Buildings Hub. The EEB Hub is a DOE Funded Research Center. The reported items were developed in a joint effort of the Department of Architectural Engineering at The Pennsylvania State University, United Technologies Research Center, IBM, and Balfour Beatty Construction, as a deliverable for the Year 2 Final Report of the Design Tools Task, 2.4.

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Executive Summary

To improve the energy efficiency of existing buildings through a retrofit process, a variety of analyses and simulations are performed for the facility being analyzed. The data used for this analysis is reliant upon the data collection process and richness of the building data. The initial assessment, often performed as a walk through review of a facility, sets the stage for the scope and direction of future retrofit assessment steps and design options. The variability in the data collection process, experience and expertise of the auditing professional, and the scope of evaluating energy conservation measures can vary drastically as demonstrated by the brief comparison of three energy audits performed for Building 101 at the Navy Yard.

To address this problem, the Modeling and Simulation team of the Energy Efficient Buildings Hub has focused on the definition of the process and data requirements of the energy auditing process. The process was mapped, with emphasis placed on the field data collection process and data requirements for downstream energy analysis. This process was used in the development of a field data collection application intended for a mobile tablet device. The application supplies the building data to analysis applications for rapid and reliable energy assessment through baseline modeling using a reduced-order modeling approach coupled with uncertainty quantification, sensitivity analysis, and economic modeling to develop preliminary retrofit feasibility options.

The audit tool development and process documentation was facilitated through a case study of the Philadelphia Navy Yard. Data was collected for utility usage for all facilities which are metered and culled to 40 buildings with one year or more of energy data for occupied facilities, with 13 of those buildings having both natural gas and electrical utility data. Inverse modeling of the 40 buildings was performed to identify overall thermal performance of their enclosures followed by more detailed R and U value coefficients for the wall, window, and roof assemblies, and uncertainty quantifications were performed on these values. These recovered values were using in conjunction with the DeepRetro tool for cross comparison of calibrated and uncalibrated model as compared to the actual utility data.

1.0 Introduction

Not only does our society have a large number of existing buildings, but we need to consider many of these existing buildings were built using outdated, energy-inefficient technologies (Benson et al., 2011). When many of these existed buildings were constructed, energy prices were much lower so little emphasis was placed on energy efficiency technologies. It is estimated that by 2030, building energy will account for half of total investment in energy supply (Tobias, 2009). With existing buildings accounting for such a large percentage of the overall energy consumption; and that percentage only expected to rise; there are a lot of opportunities for energy based retrofit upgrades. There are not only environmental benefits to reducing a buildings energy consumption, but building owners can also make a strong business case for investing in energy reduction retrofit upgrades. Reducing a buildings energy consumption helps to preserve and increase the buildings overall asset value and improve the overall bottom line of the business operations of building owners and occupants.

Task 2 of the Energy-Efficient Buildings Hub, a U.S. DOE Energy Innovation Hub, is focused on establishing the Design Tools and Methods which enable interactive, interdisciplinary team design and delivery of energy efficient buildings for both retrofit and new construction applications for “typical” commercial buildings. The focus of the Year 2 for the Energy Audit task is the development of a rapid and reliable energy audit tool, targeting a Level I Audit, with some elements of Level II audits, and a rapid screening of alternative ECMs and package of ECMs suggesting those with the highest benefits to the building owner, in terms of energy savings and payback.

Energy audits are generally considered the first step of energy retrofit projects, which paves the way for more detailed analysis along with defining the economic benefits specific to the facility. There are an increasing number of owners and facility managers turning to energy professionals to perform large-scale, multi-building energy audits, especially in commercial building sector. However, the quality of the auditing service and the implementation results vary (Coulter et al, 2012). There are still some challenges related to the energy audit process which create costs and effort barriers to customer consideration of deep retrofit for buildings.

1.1 Comparison of Independent Audit Results

Three independent energy audits were performed on Building 101. Company A performed a Level II audit while Companies B and C used the same data set from a single Level I audit. The three analyses reported widely divergent results. Although three recommended Energy Conservation Measures (ECM’s) were common to all three audits, most of the ECMs were noted in only one or two of the audits, as shown in Figure 1. In addition, the initial cost and energy and cost savings for the shared ECMs vary widely between the analyses. For instance, the condensing boiler initial cost varies between $73,950 for Company A and $31,215 for Company B. The cost savings are predicted from $ 2909/year for Company A to $1293/year for Company C. The difference in ECMs selected and the costs and savings of each leads to large differences in the total costs and savings from the proposed retrofits Table 2.

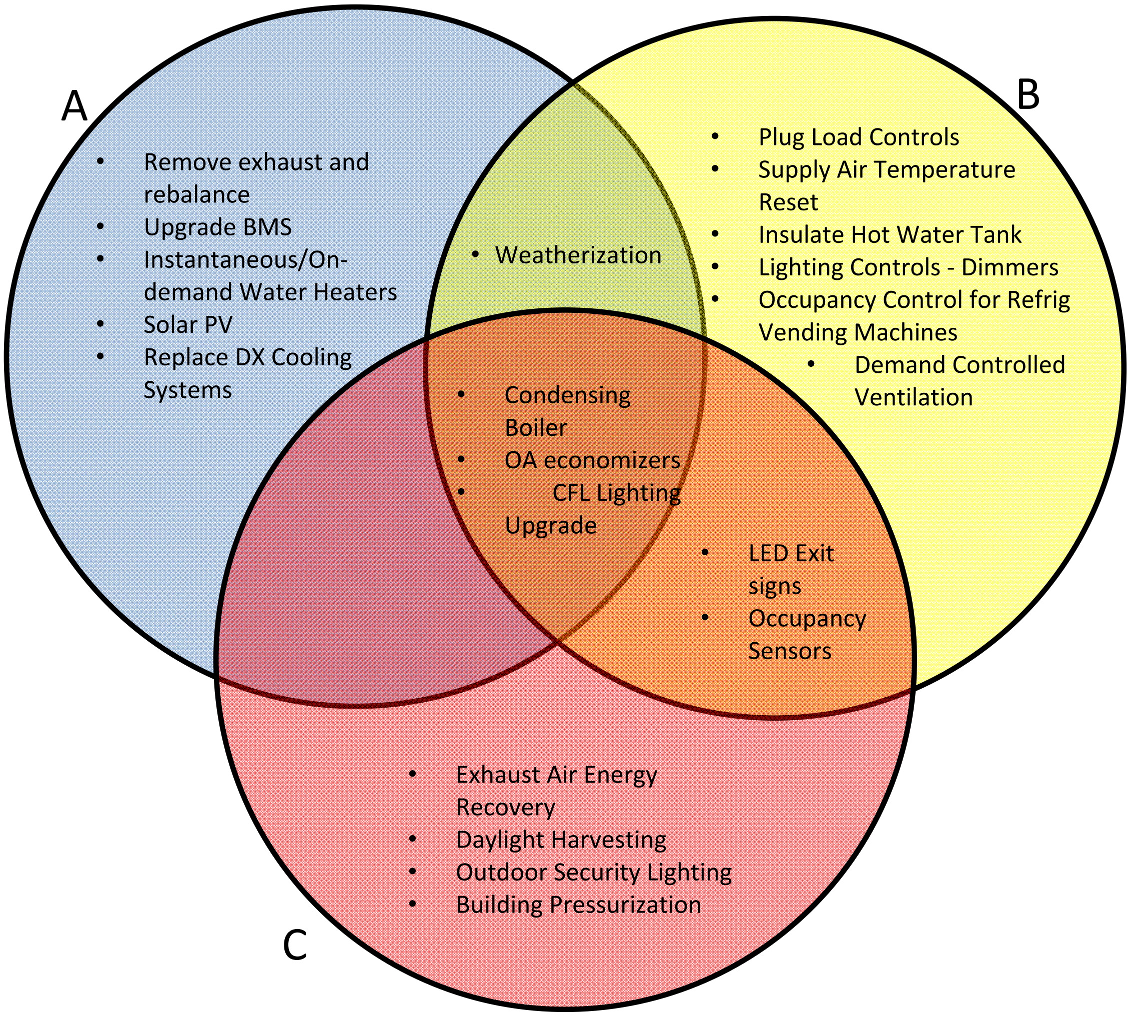


Figure 1: Venn diagram of recommended ECMs from three separate analyses by Companies A, B, and C.

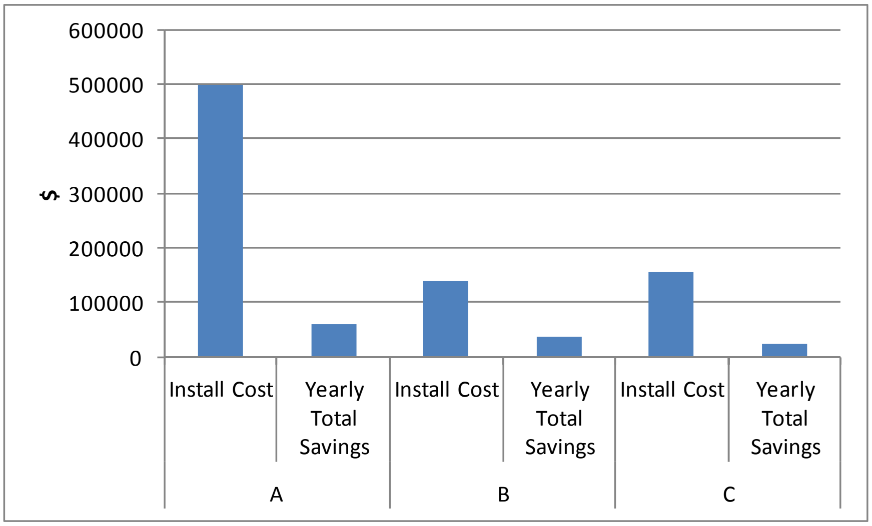


Figure 2: Installation costs and yearly savings for ECM packages proposed by Companies A, B, and C.

The differences in results could come from several sources. The list of ECMs analyzed by each company may be different. The methods and assumptions internal to the companies' processes are unclear and the sensitivity of the final result to these assumptions and the input values is unclear. The models also assume that each ECM can be calculated individually and the savings summed. The interactions between ECMs are not included by any of the three companies.

Table 1: Summary comparison of assumptions and ECM scopes & costs

Assumptions	Company A	Company B	Company C
Area [sq ft]	61700		83059 (84000)
Electricity rates [$/kWh]	0.138		0.12256
Demand charge [$/kW]	NA		4.96
Fuel rate [$/Therm]	1.456		1.41
Building model	NA		8 zone model (Trane TRACE) and excel
Calibration of baseline	NA		Monthly and yearly calibration
BMS	Old, no support available		NA
Infiltration	Low		High (1.5ACH)
Economizer	Not operating as it should		Not operating as it should
Air side control general	Not in place		Not in place
Exhaust	Operating continuously unnecessary		Operating continuously resulting in under
Lights	40% lights on during night		Most fixtures already T8

ECMs Energy savings	Company A	Company B	Company C
Airside controls optimization -Economizer -Night setback -Supply set back -Static pressure reset (DT) -Avoid simultaneous heating and cooling -Optimum start and stop	Requires new BMS Economizer separate ECM Electr. Savings: 142263+26226 kWh/yr Gas savings: 2948Therms/yr	No new BMS Temperature reset + economizer 8901+2304$	No new BMS Economizer in this ECM Electr. Savings (extra cost): -14847 kWh/yr Gas savings: 3442Therms/yr
savings in dollars per year	**$27,543.77**	**$11,205.00**	**$3,033.57**
Exhaust air energy recovery (ESN) Weatherization	Remove it Electr. Savings: 5086+52 kWh/yr Gas savings: 598+193Therms/yr	NA Dollar saving/year 10675	Balance it Electr. Savings: -20848 kWh/yr Gas savings: 6513Therms/yr
savings in dollars per year	**$1,860.74**	**$10,675.00**	**$6,628.20**
Condensing boiler	Replace Electr. Savings: 0 kWh/yr Gas savings: 1998Therms/yr	Replace Dollar saving/year 2491	Replace Electr. Savings: 1614 kWh/yr Gas savings: 766Therms/yr
savings in dollars per year	**$2,909.09**	**$2,491.00**	**$1,277.87**
Exhaust air energy recovery	NA		Electr. Savings: -546 kWh/yr Gas savings: 776Therms/yr
savings in dollars per year	**$0.00**	**$0.00**	**$1,027.24**
Lights -Occupancy sensors -Emergency Lighting Circuiting -Daylight harvesting -T12 to T8 -Retrofit Outdoor Security Lighting	Integration of control into new BMS Electr. Savings: 148977 kWh/yr	Upgrades + occupancy sensors + control 1597+1051+809+425+204+165+74$	Electr. Savings: 87058 kWh/yr Gas savings: -645Therms/yr
savings in dollars per year	**$20,558.83**	**$4,325.00**	**$9,760.38**
Instantaneous water heaters			NA
Solar PV panels			NA
Replace DX coils			NA
Attic Insulation			NA
Plug load controls	NA	8901$/year	NA
Demand control ventilation	NA	Add sensors Dollar saving/year 825$	NA

Table 2: Summary comparison of costs for shared ECM's.

ECMs Installation cost	Company A	Company B	Company C
Airside controls optimization -Economizer -Night setback -Supply set back -Static pressure reset (DT) -Avoid simultaneous heating and cooling -Optimum start and stop	Requires new BMS Economizer separate ECM Installation cost: 101844+47884$	No new BMS Temperature reset + economizer 16612+13578$	No new BMS Economizer in this ECM Installation cost: 25650$
Installation cost	**$149,728.00**	**$30,190.00**	**$25,650.00**
Exhaust fans Pressurization Weatherization	Remove exhaust Installation cost: 2546+790$	NA Installation cost: 39147$	Balance it Installation cost: 27000$
Installation cost	**$3,336.00**	**$39,147.00**	**$27,000.00**
Condensing boiler	Replace Installation cost: 73950$	Replace Installation cost: 31215$	Replace Installation cost: 37125$
Installation cost	**$73,950.00**	**$31,215.00**	**$37,125.00**
Exhaust air energy recovery	NA		Installation cost: 22050$
Installation cost	**$0.00**	**$0.00**	**$22,050.00**
Lights -Occupancy sensors -Emergency Lighting Circuiting -Daylight harvesting -T12 to T8 -Retrofit Outdoor Security Lighting	Integration of control into new BMS Installation cost: 81186$	Upgrades + occupancy sensors + control 608+636+809+856+1710+66+958$	Installation cost: 43788$
Installation cost	**$81,186.00**	**$5,643.00**	**$43,788.00**
Instantaneous water heaters			NA
Solar PV panels			NA
Replace DX coils			NA
Attic Insulation			NA
Plug load controls		29071$	
Demand control ventilation		708$	

These results are not intended to illustrate the positive or negative approaches of any of the three firms who performed the audits, but to clearly illustrate the variability in the data collection and analysis of energy saving options which are presented to facility owners.

1.2 Goal

The Energy Audit initiative weaves together process, informatics, and simulation research to focus on the initial walk through assessment of retrofit projects. While seemingly a very small step in the process, as shown in Figure 4, and demonstrated by the potential variability from the Building 101 example, the initial assessment and benchmarking of the building plays a crucial role in setting the stage for follow through of the retrofit scopes and the expectations of the owner. Estimation of energy performance of buildings during early stages of retrofit assessment is expensive and time-consuming, involving detailed metering and detailed energy modeling, especially when energy efficiency solutions with potential for 50% or more gains are evaluated (Knapp, 2006). Capabilities are needed for integrated

	Company A	Company B	Company C
Airside controls optimization			
savings in dollars per year	$27,543.77	$11,205.00	$3,033.57
Installation cost	$149,728.00	$30,190.00	$25,650.00
Simple payback	5.4	2.7	8.5
Weatherization			
savings in dollars per year	$1,860.74	$10,675.00	$6,628.20
Installation cost	$3,336.00	$39,147.00	$27,000.00
Simple payback	1.8	3.7	4.1
Condensing boiler			
savings in dollars per year	$2,909.09	$2,491.00	$1,277.87
Installation cost	$73,950.00	$31,215.00	$37,125.00
Simple payback	25.4	12.5	29.1
Exhaust air energy recovery			
savings in dollars per year	$0.00	$0.00	$1,027.24
Installation cost	$0.00	$0.00	$22,050.00
Simple payback			$21.47
Lights			
savings in dollars per year	$20,558.83	$4,325.00	$9,760.38
Installation cost	$81,186.00	$5,643.00	$43,788.00
Simple payback	3.9	1.3	4.5

information flow from the energy audit process through the feasibility analysis, to establish building energy use and for developing easy-to-use tools for estimating energy savings.

The **goal** of the Energy Audit task is to develop the process, information requirements, and tools to facilitate, rapidly estimate, and define the energy savings and economic impacts for conventional and deep retrofits at the initial walk through stage, to support retrofit decision making.

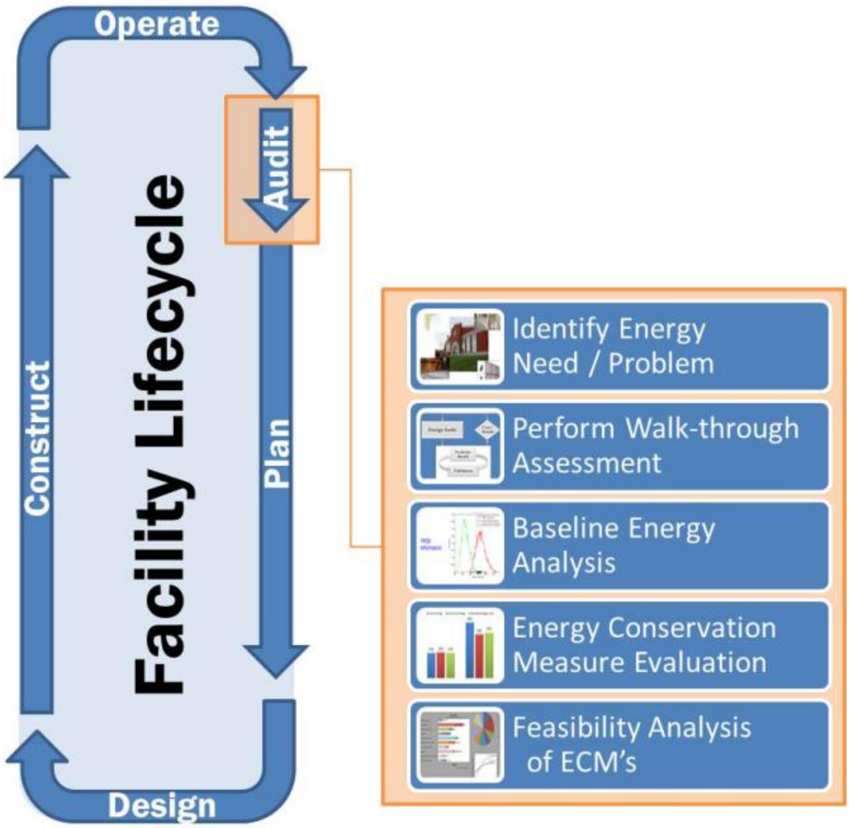


Figure 4: Alignment of Energy Auditing in the Facility Lifecycle

1.3 Work Scope

The Energy Audit tool is not a single software or device, but is developed as a tool-chain of data collection and analysis components to allow improved reliability of information flow while maintaining flexibility in the process. This report demonstrates the use of the tools and workflow analysis for the audit process and data requirements that were integrated using the Navy Yard campus as a case study. In Year 2, the team refined the analytical tools and cross compared the potential tool-chain integration based on the Navy Yard facility data collected. The team also defined the energy audit process and downstream data requirement alignment with the most commonly used energy modeling tools. In addition, an initial data collection interface, using the iOS platform, was developed to streamline the field data collection process and complement the tool-chain.

1.4 Development Methods

The tool-chain was developed and refined using the following methods:

- Literature review and content analysis techniques were used to identify and compare the software data requirements;
- An industry workshop was used to develop the process model and observational studies were performed to validate the defined processes;
- Case study analysis of the Navy Yard campus and specific audits of select buildings.

2.0 Integrated Audit Workflow and Case study

The intent of the tool-chain approach for the audit process is to, in the long term; integrate with the design tools platform which is the overall Objective of the Design Tools task. The efforts in Year 2 are focused on defining and testing the interaction amongst the tools specific to the initial assessment, data collection, and feasibility analysis aligned under the Energy Audit process. Figure 5 shows an initial architecture design of the platform, in which a database employs cloud services as a mediator for integration. Audit data collected with the iPad tools and building energy usage data are published in the database through web services. Both the inverse modeling and Deep Retro tools can be deployed on the cloud as services and interact with each other through the database (retrieving required data and publish their results). Finally, users can, on their networked enable devices, visualize building data and reports from analytic modules, and conduct what-if analysis and customize portfolio comparison.

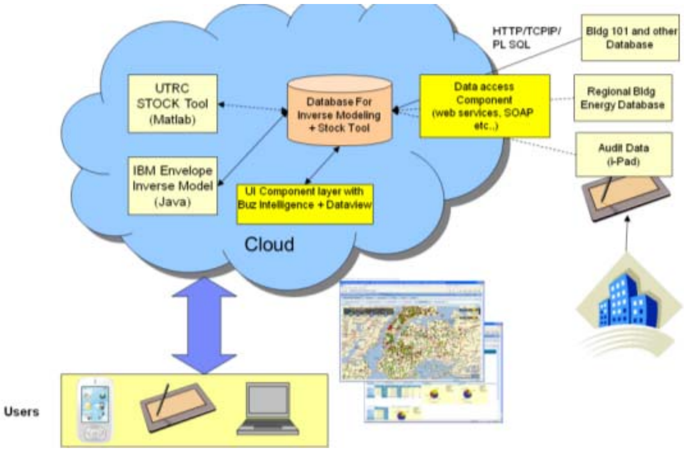


Figure 5: Architecture for audit database and tool integration

2.1 Tool chain workflow

The interaction of the tools within the Energy Audit workflow use the elements and analyses to identify the buildings and benchmark their performance using inverse modeling techniques, then the data can be used to define default values for system performance traits which are difficult to measure in situ during the assessment of the building, such as a building enclosure's effective thermal performance. The iPad and the audit application are then used to perform the on-site assessment to capture the building data. The data is fed downstream to the DeepRetro tool for performing the Baseline and Energy Savings potential using rapid, pre-defined conservation measures. The data is coupled with economic data to develop financial outcomes and feasibility data to provide consistent reliable analysis of a simple data scope from the on-site assessment.

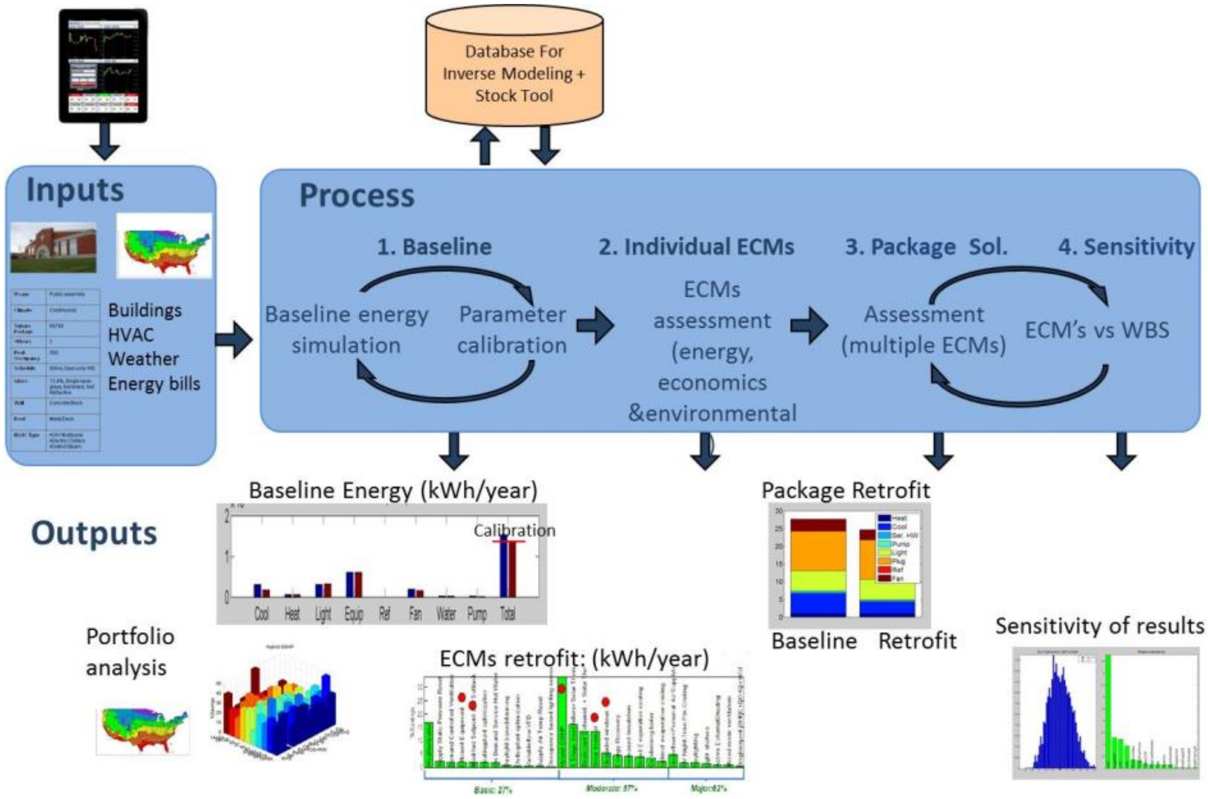


Figure 6: Process of data collection and analysis among the audit tool chain.

2.2 Philadelphia Navy Yard Case Study

To demonstrate the process, campus and building analysis tools, a case study approach was used, leveraging the Philadelphia Navy Yard as a test bed for auditing processes and simulations. The Philadelphia Navy Yard contains more than 150 buildings, though not all are currently in use. In addition, because the building served as a naval base, not every building has a separated meter for gas or electrical utility data. The process began by collecting the overall data available regarding utilities, then examining that data and narrowing the analysis potential based on the available data.

2.2.1 Data collection

Of the 84 buildings at the Navy Yard with (some) utility data, 79 had electricity consumption data and 17 had natural gas data. Within this data set, the buildings were refined to a set with a minimum of one year of utility data. This resulted in 40 total buildings with usable data, including 13 buildings with both electrical and natural gas data sets.

Using the initial data analysis, 10 buildings were selected for walk through audits by the team using traditional documentation, to capture additional detail about the systems, use, and schedule of the facility. The 10 buildings were analyzed at the systems level. The 10 buildings, shown on the map in Figure 7, are among the 13 with both electrical and natural gas data, to allow for validation and calibration of analysis with full comparison of incoming utility data.

Figure 7: Aerial photograph of Navy Yard showing locations of audited buildings.

The process used to collect the building characteristics was captured and refined during this process. The buildings audited had a variety of sizes and uses as shown in Table 3. Of these buildings, two buildings (Building 1 and Unique Industries HQ) were not easily available for walk-through data collection and could not be modeled for comparison to the utility data.

Table 3: Characteristics of audited buildings

Bldg #	**Area (sq ft)**	**Number of Floors**	**Use**
1	52866	2.5	Office
3	51905	1	Non-refrigerated warehouse
6	43241	3	Office
68	8320	1	Office/Industrial
69	4235	1	Industrial
100	37473	3.25	Office
101	61700	3.4	Office
623	3681	1	Café
694	136621	1	Non-refrigerated warehouse
Unique Industries	35000	3	Office

Further information about the analysis of each building can be found in the Appendix A.

2.2 Inverse Modeling

The focus of the inverse modeling tool is to estimate buildings' thermal parameters from limited data, such as monthly utility data, weather data and simple building geometry data. The parameters to be recovered from the inverse modeling include thermal resistance of wall and roof, thermal transmittance of window, and air infiltration rate through the building envelope. Starting with dynamic equations of energy and mass balance, we derive a static model by integrating the equations over different time periods with thermal requirements (An et al. 2012). Coefficients of terms in the model are associated with physical properties of buildings, including thermal resistance and heat capacities of walls, roof and windows. Combining with building dimensions and dynamic weather data, the monthly energy usage data is used to estimate the overall heat transfer and solar contribution parameters. A clustering algorithm is then applied on all buildings under study to segment them into certain groups based on similarities of building parameters. Finally, regression analysis for each group separates the overall heat transfer and solar parameters into R-values for wall, roof and window. Figure 8 shows an overview of inversion procedure.

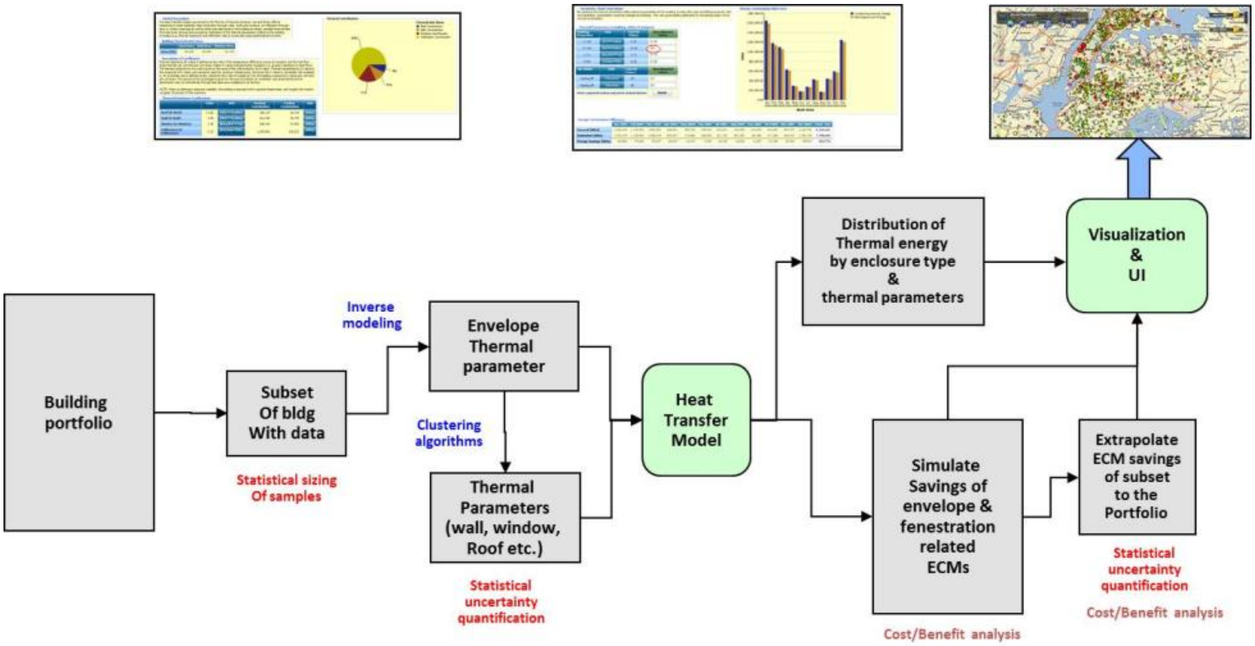


Figure 8: Inverse Modeling Process

Starting with the collected building information with both static building characteristic data and dynamic energy usage data, we select buildings with reasonable data quality, i.e. buildings with energy consumption data correlated with local weather conditions. Applying the static model mentioned above on the selected buildings, we can estimate the overall effective insulation coefficient (R-value) of each building. Following the initial R-value determination, the more details R-Values for walls, roof and windows are estimated among the clusters of similar buildings, which are identified by the clustering algorithm. Uncertainty of the recovered parameter values are also quantified from its variants in a cluster with statistical analysis, which will be described below.

With these recovered values, we calculate and show energy usage distribution by different envelope components and also calculate an initial potential energy savings that can be obtained from the envelope related energy conservation measures.

The inverse modeling approach was applied on buildings in the Navy Yard of Philadelphia. Two year's (2010-11) monthly electricity usage data were collected for 79 buildings. Additionally, annual gas usage data of 17 buildings (from those 79 with the electricity data) was also collected. We first analyzed this data to check usability. Specifically, we fit data with the following regression model

Equation 1: Regression model for testing usability of utility data for inverse modeling

$$E_t = C + \lambda_c \cdot CDD_t + \lambda_h \cdot HDD_t + \varepsilon_t .$$

In the formula, shown in Equation 1, t is for time-period, CDD is cooling degree days, HDD is heating degree days, and coefficients C, λ_c, λ_h are to be determined. The value C represents a base load (independent of weather); CDD_t and HDD_t were calculated based on weather data from a weather station in Philadelphia. The purpose of this analysis is to check if the energy consumption data is sufficiently correlated with weather data. From this analysis, we identified 40 buildings with reasonably good quality electricity usage data ($R^2 > 0.3$), and 13 (of the 17 buildings with the gas data) were identified as the buildings with reasonable fit gas usage data. As an example, Figure 9 shows a building, building # 23, that has CDD and HDD fit with an R^2 value greater than 0.8; therefore this building is a good candidate for the inverse modeling analysis.

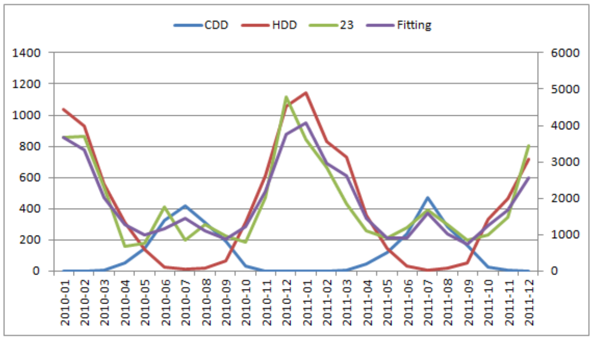


Figure 9: An Example of Correlation of Gas Consumption with Weather, Building #23 (R^2 = 0.858)

Since only 13 buildings had reasonably good natural gas annual usage data, we conducted a regression analysis on the 13 buildings to get a relationship on how natural gas usage is related to its gross squared foot. Then we extrapolated the natural gas usage on the other 27 buildings with electricity usage only. Further, assuming that natural gas is the only energy used for heating the buildings, we redistributed the annual usage into monthly usage based on HDD for those two years. Therefore, we were able to conduct our inverse analysis on 40 buildings in total.

The static inversion model is defined in Equation 2:

Equation 2: Static Inversion Model

$$
\begin{aligned}
&\lambda_{env}A_{env}(p_cCDH + p_hHDH)\\
&+\lambda_{inf}\frac{A_{leak}}{v}(p_cECHDH + p_hEHDH)\\
&+\lambda_{sol}A_{env}\int_{t_i}^{t_{i+1}} Q_{sol}(\tau)d\tau\frac{p_cCDH - p_hHDH}{CDH - HDH}\\
&+\lambda_{load}\sqrt{GFA\cdot N_{occ}}\frac{p_cCDH - p_hHDH}{CDH - HDH}\\
&+\epsilon_i\\
&=q_{effi}\int_{t_i}^{t_{i+1}} Q_{sys}(\tau)d\tau
\end{aligned}
$$

Where :

p_c, p_h	percentage area being cooled, and percentage area being heated.
A_{env}	envelope total area.
A_{leak}	leaking envelope area for infiltration.
CDH, HDH	cooling degree hour, heating degree hour.
$ECDH, EHDH$	enthalpy based cooling degree hour and heating degree hour.
GFA	gross floor area.
Q_{sol}	solar radiation energy.
N_{occ}	number of occupants in the building.
ϵ_i	error term, that captures random noise, assume ϵ_i follows Normal distribution with mean zero and variance σ^2, $\epsilon_i \sim \mathcal{N}(0,\sigma^2)$
t_i, t_{i+1}	time period t to $t+1$, e.g., $month_i$ to $month_{t+1}$.
q_{effi}	efficiency of the heating and cooling system of the building.
$Q - sys$	energy consumption of the heating and cooling system.

In this model, we included a term for infiltration, which is correlated with enthalpy based degree hours (ECDH/EHDE), because air flow from outside to inside may influence both temperature as well as humidity inside a building, while conduction through walls will only influence temperature inside building. Occupancy level was estimated using benchmark data of similar buildings from the CBECS database. Equation 3 describes the computation steps for computing the standard deviation of the recovered R-values. The upper and lower bounds generated with 95% confidence interval.

Equation 3: Statistical Uncertainty Computation

Coefficient estimate: $\hat{\boldsymbol{\lambda}} = (\boldsymbol{X}'\boldsymbol{X})^{-}\boldsymbol{X}'\boldsymbol{Y}$

where

$$
\begin{aligned}
y_i &= q_{effi}\int_{t_i}^{t_{i+1}} Q_{sys}(\tau)\mathrm{d}\tau\\
x_{i1} &= A_{env}(p_c\mathrm{CDH}_i + p_h\mathrm{HDH}_i)\\
x_{i2} &= A_{leak}(p_c\mathrm{ECDH}_i + p_h\mathrm{EHDH}_i)\\
x_{i3} &= A_{env}\int_{t_i}^{t_{i+1}} Q_{sol}(\tau)\mathrm{d}\tau\frac{p_c\mathrm{CDH}_i - p_h\mathrm{HDH}_i}{\mathrm{CDH}_i - \mathrm{HDH}_i}\\
x_{i4} &= \sqrt{GFA \times N_{occ}}\frac{p_c\mathrm{CDH}_i - p_h\mathrm{HDH}_i}{\mathrm{CDH}_i - \mathrm{HDH}_i}
\end{aligned}
$$

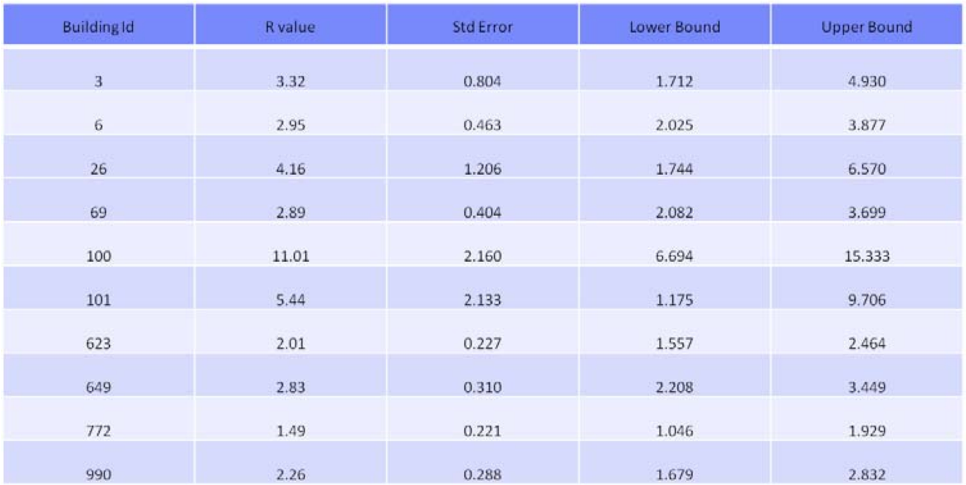
Standard deviation: $\widehat{\mathrm{sd}}(\hat{\boldsymbol{\lambda}}) = (\boldsymbol{X}'\boldsymbol{X})^{-}/\hat{\sigma}^2$

Delta method to get the standard deviation for the R-value:

$$\widehat{\mathrm{sd}}(\widehat{R}) = \sqrt{\widehat{\mathrm{var}}(\lambda)\frac{\partial \mathrm{R}}{\partial \lambda}} = \frac{\widehat{\mathrm{sd}(\lambda)}}{\hat{\lambda}^2}$$

Table 4 shows a portion of the inverse modeling results: overall envelope R-values with bound resulted from the inversion method combined with uncertainty quantification with these time-series data.

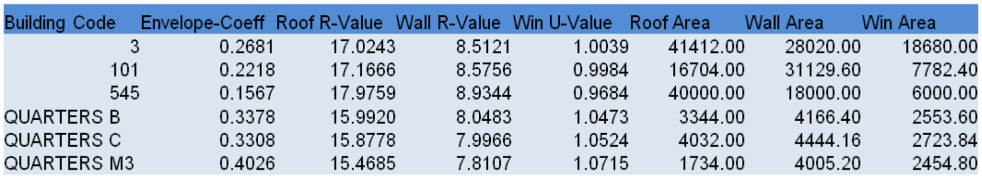
Table 4: Overall envelop R-value with bound



Building Id	R value	Std Error	Lower Bound	Upper Bound
3	3.32	0.804	1.712	4.930
6	2.95	0.463	2.025	3.877
26	4.16	1.206	1.744	6.570
69	2.89	0.404	2.082	3.699
100	11.01	2.160	6.694	15.333
101	5.44	2.133	1.175	9.706
623	2.01	0.227	1.557	2.464
649	2.83	0.310	2.208	3.449
772	1.49	0.221	1.046	1.929
990	2.26	0.288	1.679	2.832

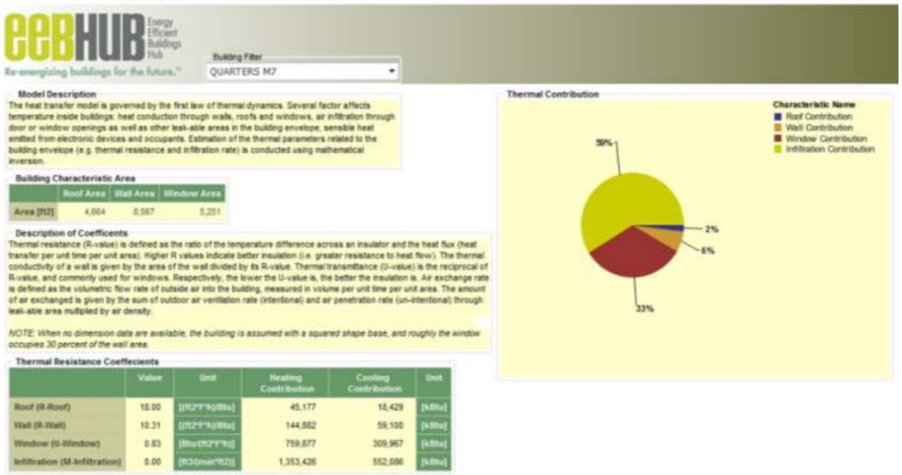
We further conducted clustering analysis among those 40 buildings, and utilized geometry data for the portfolio of buildings. Window to wall ratio for each building was assumed to be a default value of 0.38 if other data was not available, but the values were estimated from building's images for the majority of the facilities (31 of 40). Table 5 shows some results with R-values for wall and roof, and U-values for window, resulting from regression modeling of one cluster.

Table 5: Broken down R-value for wall and roof and U-value for window



Building Code	Envelope-Coeff	Roof R-Value	Wall R-Value	Win U-Value	Roof Area	Wall Area	Win Area
3	0.2681	17.0243	8.5121	1.0039	41412.00	28020.00	18680.00
101	0.2218	17.1666	8.5756	0.9984	16704.00	31129.60	7782.40
545	0.1567	17.9759	8.9344	0.9684	40000.00	18000.00	6000.00
QUARTERS B	0.3378	15.9920	8.0483	1.0473	3344.00	4166.40	2553.60
QUARTERS C	0.3308	15.8778	7.9966	1.0524	4032.00	4444.16	2723.84
QUARTERS M3	0.4026	15.4685	7.8107	1.0715	1734.00	4005.20	2454.80

A pilot, web-based user interface was developed and implemented on the cloud to display the recovered thermal parameters and energy usage distributions related to different components of building envelope, as shown in Figure 10. The user interface also provides what-if (simulation) analysis by interactively showing potential energy savings resulting from the retrofits that involve the changes of R-values, and changes of set points for heating and cooling, as shown in Figure 11.



Model Description

The heat transfer model is governed by the first law of thermal dynamics. Several factor affects temperature inside buildings: heat conduction through walls, roofs and windows, air infiltration through door or window openings as well as other leak-able areas in the building envelope, sensible heat emitted from electronic devices and occupants. Estimation of the thermal parameters related to the building envelope (e.g. thermal resistance and infiltration rate) is conducted using mathematical inversion.

Building Characteristic Area

	Roof Area	Wall Area	Window Area
Area [ft2]	4,664	8,567	5,251

Description of Coefficents

Thermal resistance (R-value) is defined as the ratio of the temperature difference across an insulator and the heat flux (heat transfer per unit time per unit area). Higher R values indicate better insulation (i.e. greater resistance to heat flow). The thermal conductivity of a wall is given by the area of the wall divided by its R-value. Thermal transmittance (U-value) is the reciprocal of R-value, and commonly used for windows. Respectively, the lower the U-value is, the better the insulation is. Air exchange rate is defined as the volumetric flow rate of outside air into the building, measured in volume per unit time per unit area. The amount of air exchanged is given by the sum of outdoor air ventilation rate (intentional) and air penetration rate (un-intentional) through leak-able area multiplied by air density.

NOTE: When no dimension data are available, the building is assumed with a squared shape base, and roughly the window occupies 30 percent of the wall area.

Thermal Resistance Coeffecients

	Value	Unit	Heating Contribution	Cooling Contribution	Unit
Roof (R-Roof)	18.00	[(ft2*F*h)/Btu]	45,177	18,429	[kBtu]
Wall (R-Wall)	10.31	[(ft2*F*h)/Btu]	144,882	59,100	[kBtu]
Window (U-Window)	0.83	[Btu/(ft2*F*h)]	759,877	309,967	[kBtu]
Infiltration (M-Infiltration)	0.00	[ft3/(min*ft2)]	1,353,426	552,086	[kBtu]

Figure 10: Web-based Portal for Thermal Parameters and Distribution of Energy Usage

Sensitivity Model Description

By updating the thermal parameters after enhancing insulation of the building envelop (through retrofitting projects), the annual energy consumption would be changed accordingly. This view gives some qualification of the saving impact on its annual consumption.

Thermal Parameters of Building (What If Analysis)

Building Properties	Unit	Current Values	New Adjusted Values
R wall	[(ft2*F*h)/Btu]	6.62	10
R roof	[(ft2*F*h)/Btu]	16.11	-1
U win	[Btu/(ft2*F*h)]	1.04	-1
M inf	[ft3/(min*ft2)]	0.00	-1
Set Points	**Unit**	**Current Values**	**New Adjusted Values**
Cooling SP	Fahrenheit	65	-1
Heating SP	Fahrenheit	65	-1

Enter adjusted values and press Submit Button

Energy Consumption Difference

	January	February	March	April	May	June	July	August	September	October	November	December
Current [kBtu]	670,698	471,104	237,920	24,835	149,420	207,452	286,626	225,214	147,815	97,442	242,396	394,861
Estimated [kBtu]	634,119	445,409	224,943	23,480	141,271	196,137	270,993	212,931	139,753	92,127	229,175	373,325
Energy Savings [kBtu]	-36,580	-25,694	-12,978	-1,355	-8,150	-11,315	-15,633	-12,283	-8,062	-5,315	-13,220	-21,536

Figure 11: Web-based Portal for Simulation and Sensitivity Analysis

2.3 Audits of select buildings

The audit and analysis process developed consisted of several steps: defining the data required, collecting the data and processing it for use by the DeepRetro tool, and finally analyzing the building data to generate baseline and retrofit energy use profiles and energy savings estimates. These steps are described in more detail in the following sections.

Data Requirements

The data needed to model a building's energy usage profile and make projections about the energy saving measures is defined by the input requirements of the DeepRetro tool. The tool has the potential for the auditor to provide approximately 100 parameters, derived from building characteristics, to create a representative model. It is possible to provide fewer inputs, in which case the tool will populate unknown but necessary parameters using data derived from similar buildings within the CBECS dataset. However, as more of these inferred parameters are used, the model becomes less representative of the actual building baseline being modeled and more a benchmark representation of a ‘typical’ building of the same type, location, and usage.

The information required by the DeepRetro tool includes aspects of the building and all of its subsystems, including:

- *Location*: used to determine solar radiation angles and weather
- *Geometry*: needed to specify the building plan form shape and dimensions
- *Envelope*: needed to determine the thermal properties of the exterior surfaces and the radiation transmittance characteristics of the windows and other transparent elements
- *Schedules of operation*: needed to set opening and closing times which determine when lights, plug loads and HVAC equipment are operational
- *System Setpoints*: used to specify the heating and cooling demands of the building
- *Energy usage*: used to input the current energy use of the building derived from utility bills
- *HVAC systems and performance*: needed to input the primary type of the HVAC system in terms of the method of heating and cooling delivery and the performance of that equipment.

Data Collection

The data requirements for DeepRetro, having been defined in the previous section, it is now necessary to design a data collection process to meet those requirements as efficiently as possible. DeepRetro models a building as a single thermal zone and in the current version of the tool data is input to reflect this modeling approximation. However, the building audit process produces simulated building information at a much greater level of detail, which must then be abstracted to produce data at the same level of fidelity as the DeepRetro tool. For example, the building auditor may count the number of windows and measure the dimensions of each window size. The tool only implements the concept of total window area by orientation, which must be computed by aggregating the individual window size and orientation data into the necessary parameters. The tool requires a user to input a single lighting power density for the entire building. But, this must be derived from lighting data about multiple representative individual rooms to avoid cataloging every lamp and fixture in every room. Energy Auditor and Facilities Engineering judgment necessary in understanding which spaces in a building are typical and how to weight their lighting power contributions as a fraction of the overall LPD of the whole building.

While a building walkthrough is most useful in understanding current conditions in the building, other sources of information can also be useful. These sources include as-built drawings and specifications from which building dimensions may be derived. Drawings and plans may, in fact, be the best source of dimensional information. However, as the UTRC team discovered, it is also possible to get acceptably accurate exterior wall and window dimensions by doing direct measurements. We found that a laser rangefinder in triangulation mode was fast and effective in making all types of measurements of exterior wall and window dimensions.

While building geometry is relatively easy to define based on drawings and observations, the thermal properties associated with the building envelope are difficult to identify. The exterior and interior layers of a given wall are typically readily identifiable, but it is not possible to know the details of any interior layers and their condition. Condition is particularly important with respect to insulation as certain types degrade over time as they settle or are exposed to moisture. In addition, the effect of thermal bridging is largely unknown and difficult to quantify. For these reasons, the UTRC team feels that, when possible, the thermal properties of the envelope should be calibrated using a model in conjunction with monthly or annual energy use data. This is the approach incorporated into the DeepRetro tool. Without calibration, the envelope thermal properties will always have high levels of uncertainty. The inverse model by the IBM team described earlier in this report can also provide the thermal properties of building envelope.

The UTRC team found that information about the building and HVAC schedules of operation was best determined by interviewing the building facilities manager or equivalent. Temperature setpoint/setback schedules were determined through interviews and sampling the individual room thermostats for additional ground truth data. Nominal HVAC performance parameters were determined from the equipment nameplate data in addition, when available, to manufacturer's published performance data derived from the equipment model number. Nameplate data obviously does not account for degradation of equipment performance due to age and lack of maintenance so calibration of the HVAC performance parameters using DeepRetro simulations in conjunction with actual energy use from utility bills is an important analysis step. Without calibration, the only way to ascertain the actual performance of each component of the HVAC system would be to install instrumentation to measure input and output power as the equipment operates. This is feasible, but clearly beyond the scope of a Level I audit, which this tool primarily addresses

Integration & Comparison of Simulation techniques

A comparison was made of modeling results using the inverse and DeepRetro enclosure (U) values. Buildings 3, 6, 68, 69, 100, 101, 623 were selected because they have both electric and gas data and they overlap with buildings modeled by both tools. All the buildings use natural gas heating and electric cooling. Collected perimeters and heights were used to update the inverse modeling assumptions originally employed in the inverse modeling analysis. The enclosure performance values from the inverse modeling approach were then input into the DeepRetro tool. In general, UTRC uncalibrated predictions are similar or better in accuracy to IBM reverse modeling results when compared with measured utility data. One major reason for this difference is likely due to the limited data set used for the regression and clustering analysis performed in the inverse modeling analysis. Due to the need for large datasets for significance and model fit in the analysis of the enclosure values, and the use of only 40 total buildings in the data available from the Navy Yard, the thermal parameters currently determined could be refined as a larger dataset is collected. For example, in Figure 11 and **Error! Reference source not found.**, the calibrated and uncalibrated UTRC annual energy use predictions are compared to the predictions with the IBM U values for building 100.

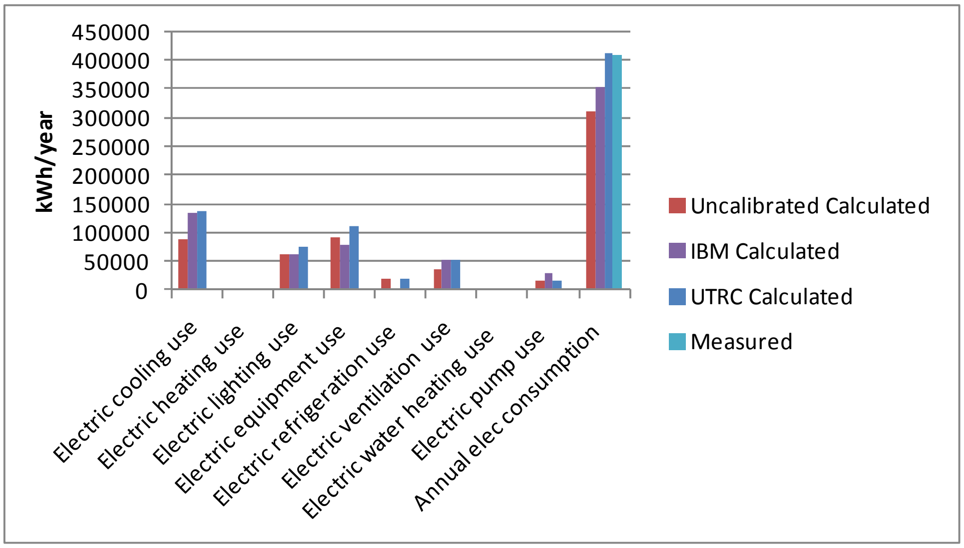


Figure 12: Comparison of electricity use predictions with IBM and UTRC U values for Building 100.

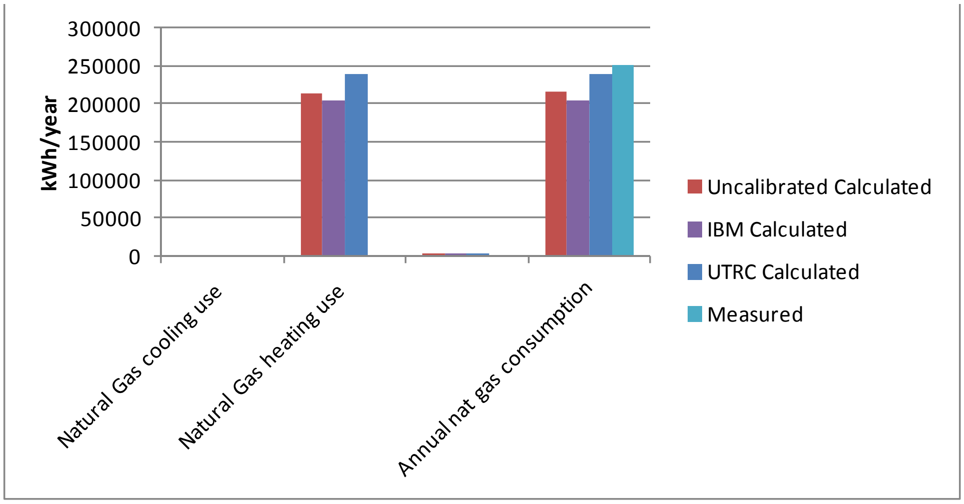


Figure 13: Comparison of natural gas use predictions with IBM and UTRC U values for Building 100.

The outcomes indicated for Building 100 are an informative example where the raw electrical performance, even given the limited dataset employed thus far, provides potential added value at the initial data collection phase before the DeepRetro tool may be calibrated. Similarly analysis of load dominated buildings, such as building 623 shown in Figure 13, provide value from the inverse approach because of less common internal loads (623 is a restaurant with high heat loads year round).

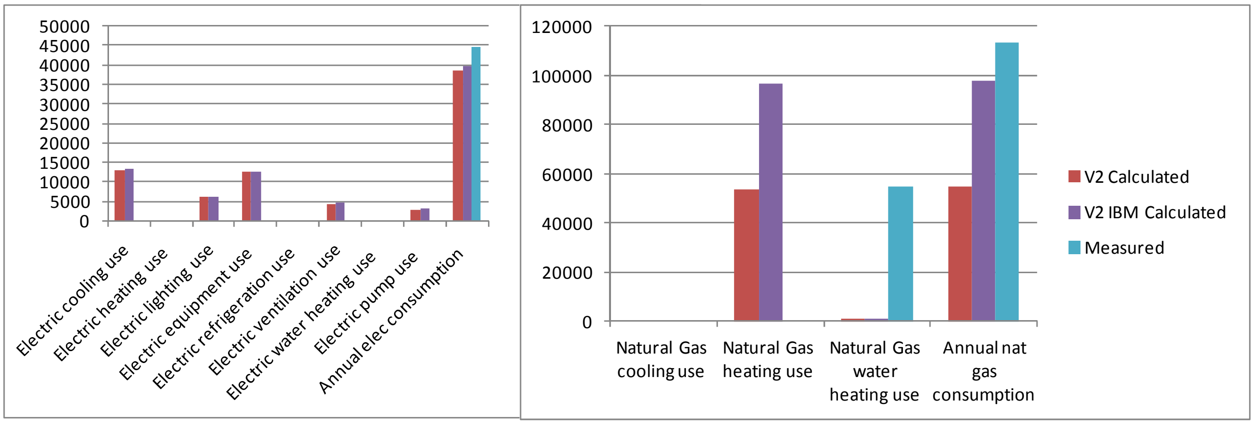


Figure 14: Comparison of uncalibrated analysis to inverse modeling performance for Building 623

2.4 Conclusions

In general, UTRC uncalibrated predictions are similar to the IBM inverse modeling results when compared with measured utility data. The difference in accuracy of results may be due to different modeling approaches and definitions of U values in the reduced order UTRC model and in IBM's inverse model. When sufficient detail of the baseline energy performance and use of the building is collected for a building, such as Building 100, the values from the DeepRetro tool were more closely aligned to the measured data. In addition, the automatic calibration function for the buildings using the utility data history allowed annual building performance within 10% of the actual performance.

In cases where data collection were more difficult to collect, and noticeably in internal load dominated buildings such as building 623, the values from the inverse model may offer added value. IBM's inverse model accounts for the aging and degrading conditions of building enclosure performance based on inverse modeling of performance across longer periods which are difficult to capture in a walk-through audit scenario.

3.0 Process, Data Requirements, and Tool Development

Reducing a building's energy can reduce operating and maintenance costs, thereby saving an owner money over time. The decision on the scope of retrofit upgrades to implement on a project is most commonly dictated by investments that have low payback periods or high returns on investments (ROIs). Some of the most common retrofit upgrades include improving building insulation and lighting system upgrades. These building upgrades are often employed due to the fact that they are relatively easy to install and offer short payback periods. The predictability of the ROI of the insulation and lighting upgrades also makes these two upgrades favorable (Benson et al., 2011).

Energy auditing is an important because it allows an owner and the individual studying the building to gain a better understanding of how the building is performing and operating; and gauge which potential retrofit options are appropriate. The energy auditing process is utilized to collect data about the building systems, geometry, usage, and energy consumption of a given facility. The data collection from the audit process allows somebody, often an engineer, to perform an energy analysis to evaluate potential energy savings and retrofit feasibility. From the audit process building owners make the decision of whether they are going to pursue a more detailed energy study, energy model, or particular retrofit scope.

This section will provide an overview of the research performed to map the energy audit process, explore the data requirements of energy audits for defining a standard information exchange, and the alignment of this data and process to the inverse modeling and reduced-order model analyses employed through the energy audit initiative.

3.1 Audit Process Development

The energy auditing process is utilized to collect and analyze data about the building systems, geometry, usage, and energy consumption. The type and amount of data that is collected during an energy audit varies depending on the level of audit which is being performed, and because the process for performing an audit is not standardized critical data is sometimes overlooked (Deru, 2011). Energy audits play a critical role in analyzing a buildings energy performance and to identifying potential energy conservation opportunities. While there are industry standards for various "levels" of energy audits, there are many different approaches to performing an audit. "There is a direct relationship to the cost of the audit (amount of data collected and analyzed) and the number of energy conservation opportunities to be found). Thus, a first distinction is the cost of the audit which determines the type of audit to be performed." (Thumann, page 33).

3.1.1 Background

There are three different levels of an energy audit. While different nomenclature may be used to describe the three levels: walk-through, mini-audit, and maxi-audit (Thumann, 2008); most industry members have adopted ASHRAE's naming convention:

1. Level 1 - Walk-Through Assessment
2. Level 2 – Energy Survey and Analysis

3. Level 3 – Detailed Analysis of Capital-Intense Modifications

Figure 15 shows the relationship between the three levels of the energy audits as defined by ASHRAE. Prior to performing an audit, a preliminary energy-use analysis (PEA) is sometimes performed. The (PEA) is intended to be a low-fidelity calculation that looks at the buildings overall gross conditioned floor area compared to copies of utility bills from a one to three year period (Deru, 2011).

A walk-through audit is intended to be a brief and should allow the auditor to become familiar with the facility. During a walk-through audit, if possible, the individual performing the audit should meet with the owner and/or facility operator to discuss any maintenance or operation concerns they have about the facility. A walk-through audit is intended to allow the auditor to become familiar with the facility while identifying low-cost or no-cost changes to the facility or to the operation and maintenance practices. During a Level 2 – Energy Survey and Analysis Audit the individual performing the audit is expected to collect much more detailed information about the mechanical and electrical systems installation, maintenance, and operation conditions. During a Level 2 audit, some of the systems the auditor will be examining include the lighting, HVAC, domestic hot water, envelope, plug loads and refrigeration. The auditor should be examining operation and maintenance logs and comparing the systems examined to their design parameters. A Level 2 Audit will likely involve taking some measurements. The outcome of a Level 2 Audit is a summary of the buildings current energy use, a summary of practical measures and recommended bundles of ECMs and savings, a list of investments that were ruled out during the analysis, and a list of potential capital-intensive measures that may require a Level 3 audit. A Level 3 – Detailed Survey & Analysis is a continuation of a Level 1 and Level 2 Audit and is often guided by the recommendations and findings of initial audits. A Level 3 Audit involves accurate modeling of the proposed feasible capital-intensive. A Level 3 audit may involve collecting additional data in order to produce the model and the outcome is a list of estimated cost and savings of proposed modifications and any bundled packages.

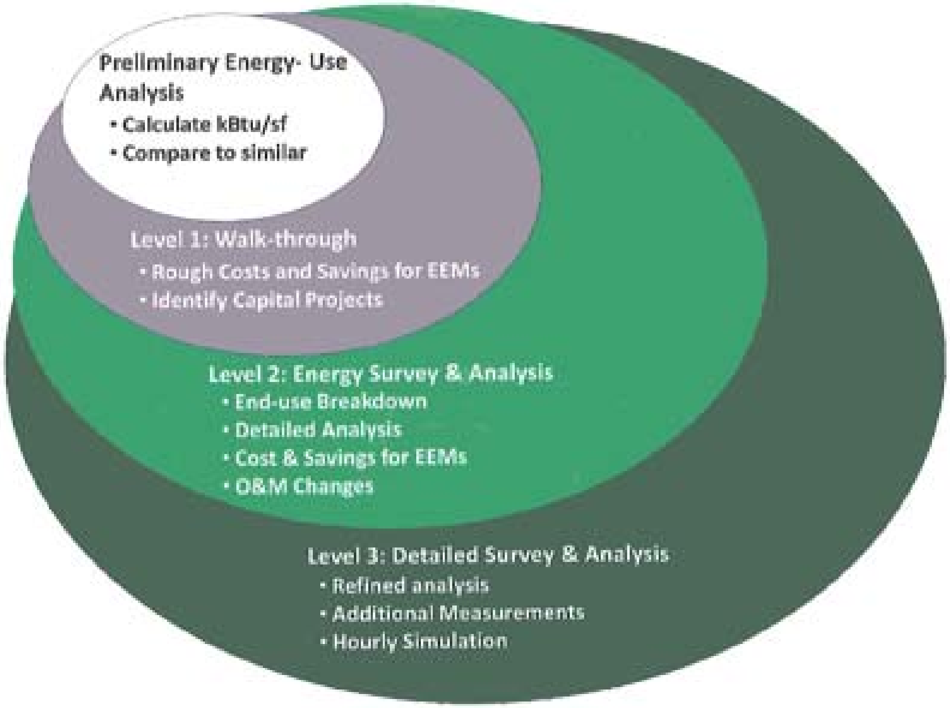


Figure 15: ASHRAE Energy Audit Levels (ASHRAE, 2004)

The energy auditing process is currently faced with many challenges. While the audit levels are clearly defined, there is much ambiguity when it comes to the process for performing the audits and the actual data that should be collected during each energy audit level. Inexperienced auditors may not know the appropriate building data to collect and examine, nor the sequence of auditing process tasks, or key stakeholders to interview, and they also may not notice maintenance or operation issues when performing the audits. The commercial energy auditor job task analysis report developed by NREL provides a detailed account of process-based tasks and associated skills and competencies needed to complete those tasks. The order and sequencing of audit task is business case and building context dependent, which can lead to uncertainty and variability in process and audit outcome. Formalizing energy audit processes is therefore a key focus to improve this critical phase of advanced energy retrofit projects.

Data collected during the energy auditing process is often used to produce energy models and perform energy analysis. If the data collected during an audit is incomplete or inaccurate, this will negatively affect the accuracy of the energy modeling results. Also, despite the fact that there are three different “levels” identified by ASHRAE, the levels are not as clearly defined in industry practice. Most companies perform a Level 1 or walk-through audit, then either a detailed audit somewhere between a Level 2 or Level 3 audit. The differences in the audit processes, each individuals differing experience level and approach to performing an audit, and the quality and variety of data collected during an audit results in different scopes being investigated and recommended to building owners.

Owners have also expressed issues with inconsistencies concerning the proposals they receive within energy audit reports. Due to the variability with the energy auditing processes each individual follows, this leads to differences in the energy conservation measures (ECMs) each company investigates, and the assumptions they make when preparing audit reports proposals. Some building owners have even reporting abandoning retrofit projects all together based solely on the variability among the proposals they received, so much so that they found it difficult not only to select a company but even to define the appropriate scope for their project.

The purpose of the energy audit process is to collect accurate data about the building which can later be used to make informed decisions about the feasibility of retrofit upgrades. A critical aspect of the energy audit walkthrough of a facility is to confirm the state of performance of the energy-related systems. The walkthrough provides key cues to the current state of building operations and provides the auditor with solution search strategies to pursue in the analysis phase of the assessment process.

All of the challenges surrounding the energy auditing process directly affect the reliability and accuracy of the energy modeling predictions. The data that is collected during the energy auditing process is used to populate energy models. Inconsistencies or failure to collect data during the auditing process is going to negatively impact the reliability of the energy models produced.

3.1.2 Methodology

To combat this variability, a generic energy audit process was developed to define the stages of audits and the data collection and analysis procedures used. The develop this process three methods were employed: 1) A comprehensive review of energy audit literature was performed to define the core steps and requirements for conducting energy audits of existing facilities. 2) A workshop was conducted with industry professionals with experience in the energy retrofit industry to map the processes, as seen from the differing points of view of the organizations involved, and 3) Observational studies were employed to validate the process used in situ of energy audits being performed.

A workshop was conducted to allow industry members to voice their issues with the current energy auditing processes.

The goals for the workshop were:

1. Define the energy auditing process through each phase of a project, and the problems and key issues, with regards to the collection of the appropriate level of information necessary to perform a meaningful audit;
2. Develop consistent process and procedures necessary to perform a screening energy audit with key attributes, ranked within each phase, to align the tool design criteria;
3. Identifying the integrated / themed attributes that impact the quality of an energy audit and the role of key stakeholders throughout the retrofit process.

3.1.3 Session 1 - Defining "The Problem": There are numerous approaches and methods used for screening audits based on tools and various retrofit objectives. It is important to identify the key issues related to these approaches at different phases of a project in order to define an integrated process. The purpose of this session was to define the major processes, critical metrics and associated problems based on business cases from different industry points of view.

Figure 16: Sub-group from the Audit Session one discsussing the draft steps identified by the group.

For the first session, the large group was divided into four break-out groups composed of representatives from different industry sectors (as shown in Figure 16). The organizational point of view of the four groups is presented in Figure 17.

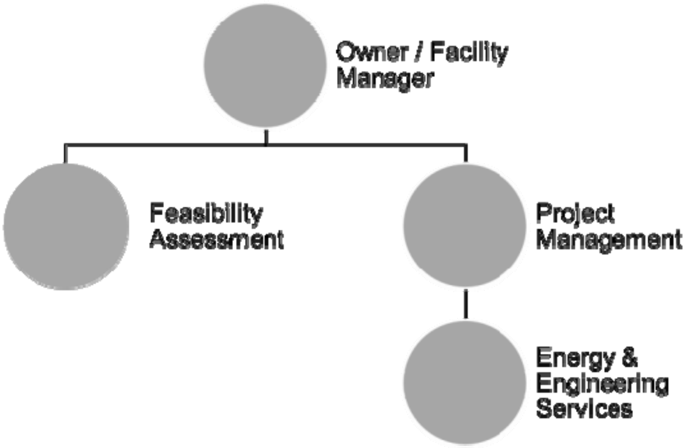


Figure 17: Breakout groups shown as an organizational chart for a project.

The groups defined the audit process and identified related problems. In order to facilitate the discussion, suppliers, inputs, outputs and customers involved in the audit process were also identified. For example, Figure 18 illustrates the input output system from the perspectives energy auditors.

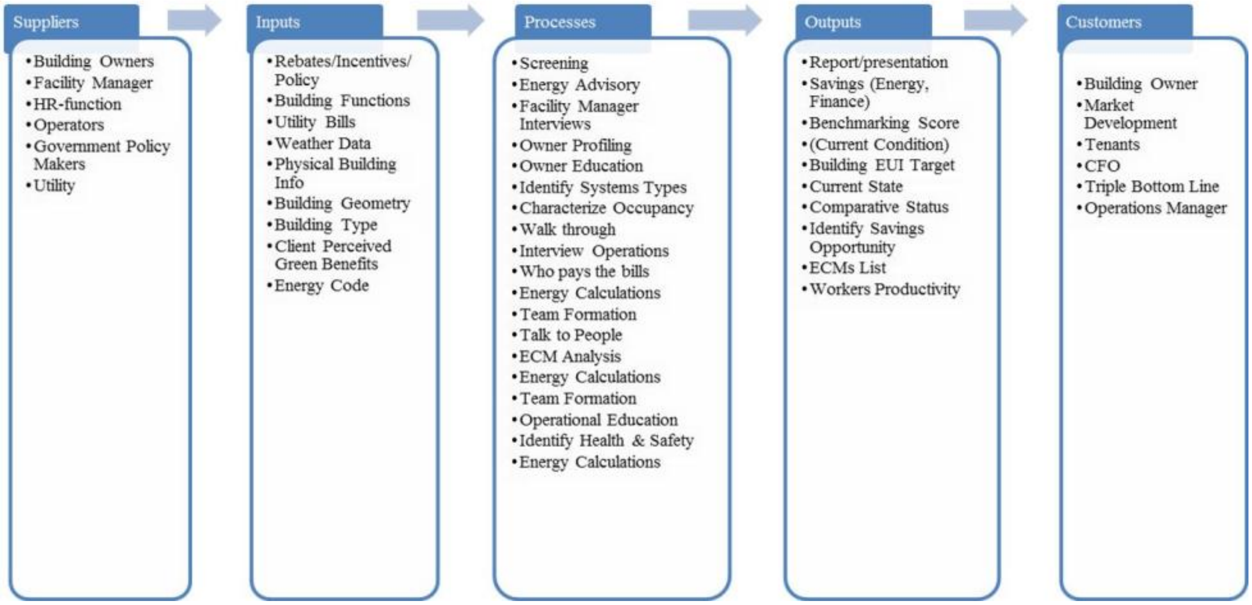


Figure 18: Result of Customer Supplier Input Output System for Energy Auditing.

3.1.4 Session 2 - Identifying Solution Attributes:

Based on the discussion in Session 1, solutions were proposed in order to solve the problems related to the screening audit process. Key attributes of the solutions were discussed and prioritized from high to low based on their impact on the process and identified problems. In order to facilitate further discussion, the themes of these attributes were used to align the solution attributes. The activities in this session were aimed at identifying potential solutions for current energy retrofit processes which rely on energy audit information.

A brief discussion was held as a large group to report back the results from the first session by each group. Based on the identified problems, four themes were identified as:

- Information Management;
- Process Quality;
- Risk and Financial Decisions; and,
- Training and Education.

For the second session, the discussion focused on the solution attributes based on the problems identified. The large group was divided into the same four groups as the first session and each group was given the task of brainstorming solution attributes. The attributes were then aligned under the four themes with rankings from low, medium and high based on their impact on the quality of the energy audit, as shown in Figure 19.

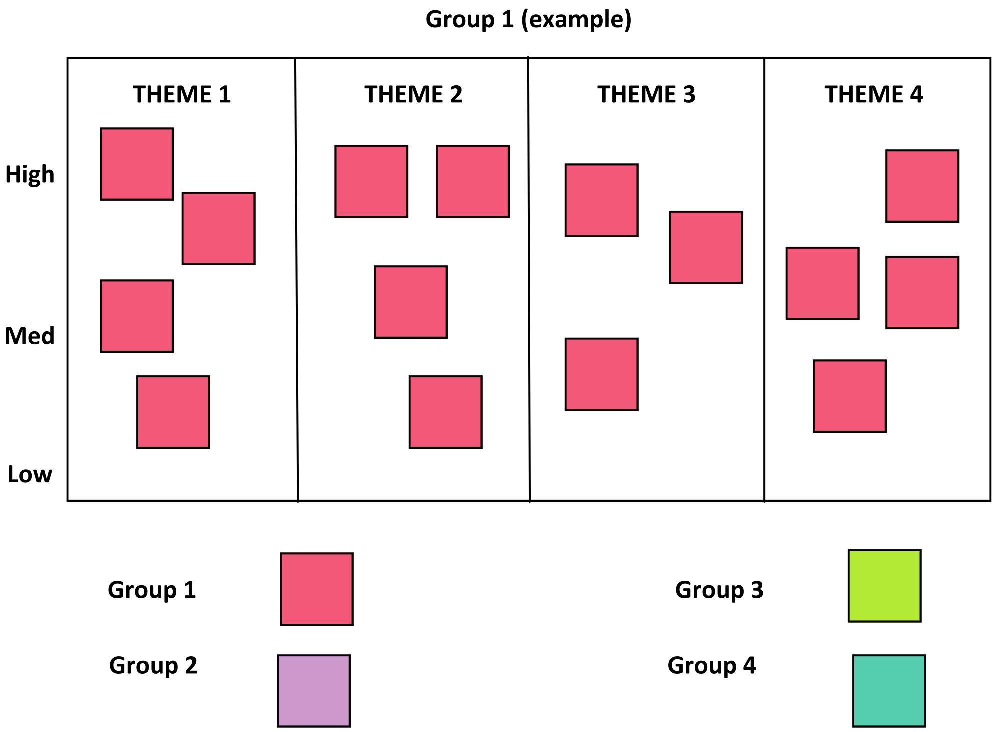


Figure 19: Session 2 Discussion Task visual.

3.1.5 Session 3 - Cross-Disciplinary Attributes:

With various sources of data and participants, it is important to integrate the screening audit process to make it efficient within an integrated solution across phases of a project. In order to develop an integrated process, there was a cross-disciplinary discussion within new groups, based on the solution attribute themes, using the attributes developed from Session 2. Potential changes in the attributes and priorities were identified from an integrated perspective.

For the third session, the discussion focused on integrated and lifecycle perspectives of energy retrofit projects. Each group was given the task of realigning and re-ranking the solution attributes from the second session for one theme. Based on the discussion, the solution attributes were evaluated by the criteria developed in the second session, with the final solution attributes matrix is shown in Table 6.

The solutions attributes performance criteria are adopted by the research team as project guidance principles for the audit tool chain development process.

Table 6: Solution Attributes Performance Criteria

Performance Criteria	Data & Information	Process & Workflow	Feasibility & Finance	Workforce
Accessible	℗	○		●
Collaborative & Engaged		●	○	℗
Committed				℗
Competent				℗
Cost Effective	○	●	℗	○
Comprehensive	℗	○	●	
Efficient		℗		●
Reliable	℗	○	●	○
Standardized	℗	●	○	○
Transparent	℗	●	○	
Tangible	℗	●	○	
Usable/Informative/ Educational	℗	○	●	○

Highly Relevant	℗
Relevant	●
Somewhat Relevant	○

3.2 Developed Energy Audit Process Model

The Business Process Model and Notation (BPMN) is a modeling notation for graphical representation of a business process; formerly referred to as Business Process Modeling Notation (OMG, 2011). BPMN bridges the gap from the business process design and implementation. The goal of BPMN is to create a notation that is understandable by business users, from the design of the processes, to the implementation of the technology to follow those processes, and finally, to manage and monitor the processes (OMG, 2011). There are mainly four main diagram elements types of element in BPMN, which are – actors, processes, connections, and artifacts (IDM technical Team 2007).

The energy audit process corresponds to the Planning Phase of the Integrated Building Lifecycle Process Model, initially developed in BP1 under the Process and Tools task of the EEB Hub (Development, 2012). The Audit Process, more specifically, aligns with:

> ***HVAC Systems***
>
> The Planning Phase is similar to the traditional construction/building planning phase. In this phase, the owner's needs and requirements are studied and defined. The Owner's Project Requirements (OPR) are established and project constraints are studied. The constraints can be physical, such as the size and type of the area and the space program; technical, such as the type and number of outlets and materials; or financial, such as investment budget or Life Cycle Cost (LCC).
>
> Conduct Energy Auditing of Target Building: In energy efficient building renovation projects, assessing and analyzing current energy use and flows of the target building need to be conducted to identify opportunities, establish appropriate goals, and develop corresponding design (Development of…, 2012).

Conducting an energy audit typically focuses on the technical feasibility of the energy retrofit options available to a facility owner; however the technical feasibility must be couched in terms of the operational and financial feasibility considerations. The audit and technical feasibility was defined in 6 primary steps, as shown in Figure 20: Energy Audit Process Overview:

Discovery – Project Goals and Needs: This is the process of defining the scope and targeted outcomes of the energy audit to align with the intended use of the facility, depth, or level, of audit data collection, and constraints for the retrofit scope feasibility analysis

Pre-Audit Energy Use Analysis: This step is the initial collection and review of project data, such as drawings and utility data, to inform the auditor of the systems, building characteristics, and use.

On-Site Assessment: This is the process of visiting the facility being assessed to collect data regarding the building geometry, systems, and use for developing baseline energy use and identifying opportunities for energy savings.

Energy Survey: This is the process of collecting the operational information of the building including both the technical operation data regarding maintenance and system performance along with user occupancy and behavior data.

Modeling and Analysis: This is the process of developing the baseline energy performance and energy savings potential through modeling of the building's systems and performance.

Feasibility and Packaging: This is the analysis of the modeling outcomes to identify recommendations for the facility owner regarding the financial considerations to accompany the single or packaged energy saving measures.

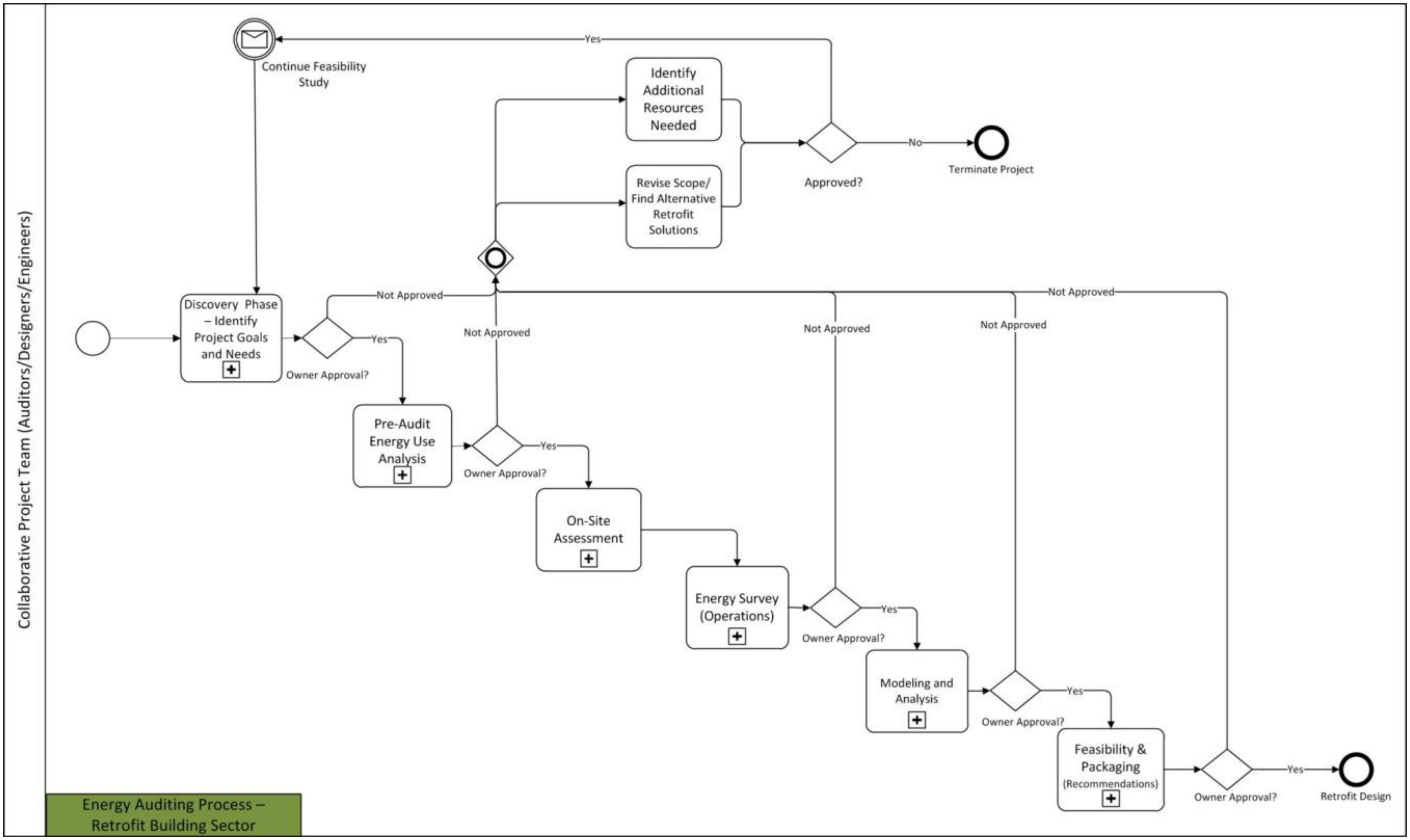


Figure 20: Energy Audit Process Overview

The audit and technical feasibility was defined in 6 primary steps, as shown in Figure 21: Building Site Assessment Process:

Collect Exterior Building Geometry and Performance Data: This is the process in which the auditor measures and documents the exterior features of the building, typically including wall, window, entry, and roof geometry and assembly characteristics.

Collect System Central Plant Data: This is the collection of the equipment data of the buildings mechanical, electrical, plumbing and fire suppression, along with any additional systems to support the buildings intended purpose.

Collect Building System Terminal Unit Data: This is the collection of the distribution and terminal equipment data at the occupied and unoccupied spaces within the building.

Collect User Lighting and Plug Load data: This is the collection of the lighting and plug load equipment data of the end-user functional spaces within the building.

Collect Interior geometry and characteristics: This is the process of collecting the geometry attributes within the user spaces which may influence the energy use within the space, such as the depth of walls from the exterior and height and size of interior window openings and presence of interior shading devices.

Collect Building Control System Data: This is the process of collecting the system operational settings, such as the user space thermostat temperature setpoints, the system distributed temperature setpoints, control setbacks.

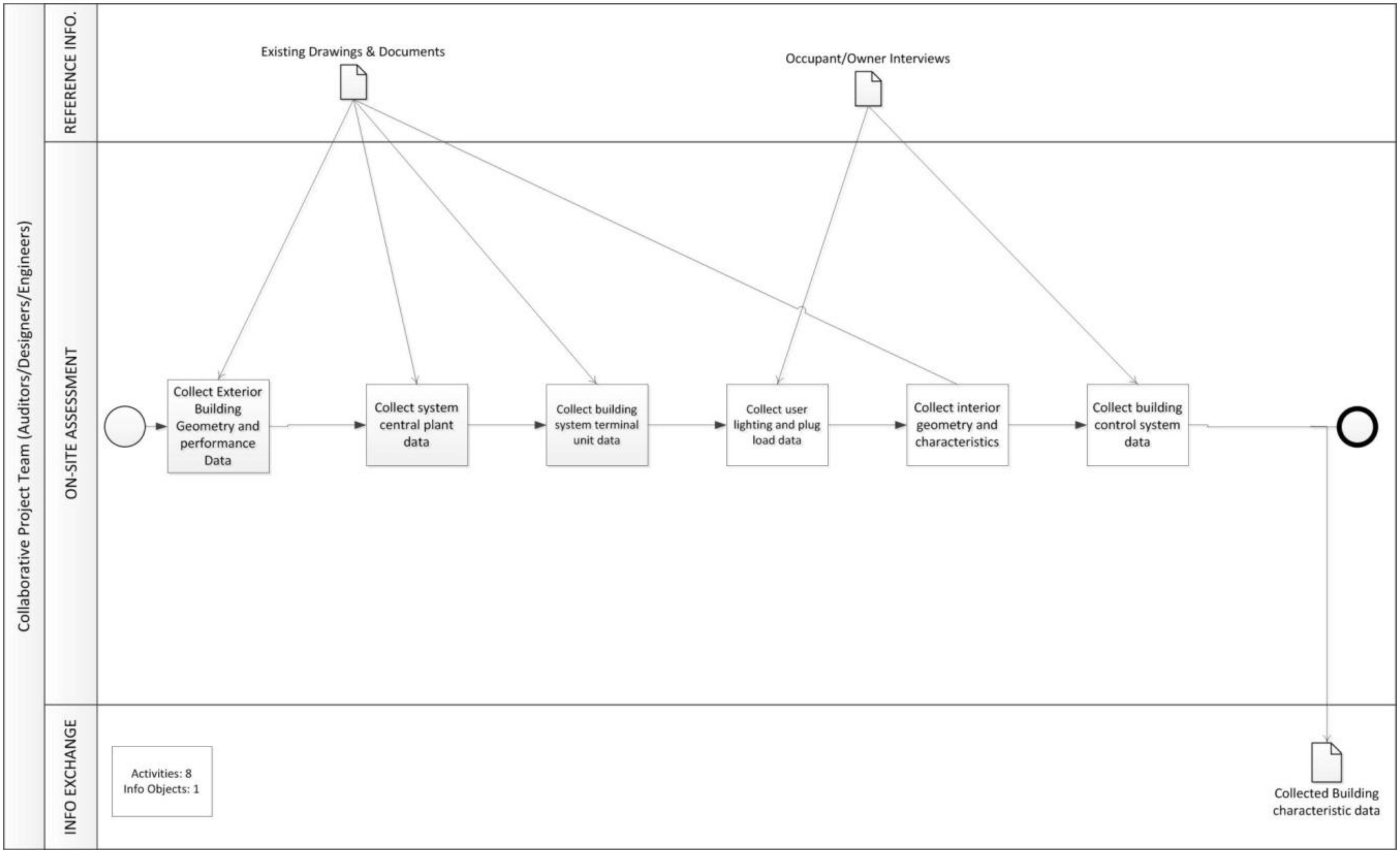


Figure 21: Building Site Assessment Process

3.3 Data Structure Analysis

3.3.1 Defined Data Structure Scope

Data selected for energy analysis will significantly impact the auditing results (Zhu, 2005; Raham, et al., 2010). The whole data collection and analysis process can take significant time and resources for more detailed data collection and analyses (Knapp, 2006). Misinterpretation of the data, erroneous assumptions and the collection of unnecessary information are common mistakes due to a lack of an integrated and standardized energy auditing data structure. Moreover, current energy modeling softwares are developed to simulate the energy loads of new buildings, whereas only comparative results are expected for existing building retrofits (Waltz, 2000).

As part of the research process, currently available energy audit data structures were analyzed to define a complete and consistent category. The categories were compared with the standardized data input of energy modeling in order to determine the information exchange requirements from energy audit to energy modeling.

The goals of the data structure work include:

1) Define a consistent data structure for an energy audit;
2) Compare the standard audit data to energy modeling inputs for the most commonly used energy modeling tools; and
3) Cross compare the data collected under the current energy audit walk through analysis tool for alignment with the identified standard data.

3.2.2 Data structure

There are some standards available on the data structure of commercial energy audits. The purpose of these data structures is to assist building energy auditors collect data required for complete energy and financial analyses. The *Procedures for Commercial Building Energy Audits* of ASHRAE provides guidelines for data collection forms along with the procedures, which aligns with the three levels of energy audits; level I, level II, and level III.

The Rocky Mountain Institute (RMI) provides a data collection template for a detailed energy audit process. These sample forms are categorized into seven sections based on different construction systems. Each section contains several sample forms to facilitate the data collection for energy and financial analysis. The categorization of these data structure is shown in Table 1.

Table 7: Templates and softwares selected for data structures comparison

Energy Audit Standards	Energy Modeling Tools
ASHRAE Procedures for Commercial Building Energy Audits	eQuest
RMI Energy Audit Template	Energy Plus
	Trane Trace 700
	HAP

Information Exchange Descriptions are methods that identify the information content of an exchange. They identify which objects, processes properties, relations and classifications are both relevant to the receiving (importing) application and available in the sending (exporting) application. Information Exchange Requirements are specified in terms of the information items they must carry, fully detailing those outlined in the exchange descriptions (Eastman et. al, 2011).

The purpose of defining information exchange requirements is to specify the information items and attributes in sufficient detail in order to facilitate the communication process. As previously discussed, there is not a standard information exchange requirement for energy audits. This is significant because, despite the detailed efforts focused on interoperability of software during the design phase of a project, significant rework in terms of data collection occurs due to the lack of re-useable data from the audit process.

Energy modeling is a process used for analyzing the energy performance of buildings and with the intent of evaluating architectural and/or mechanical designs through some energy simulation. Energy modeling is applicable in new construction, major renovation, and in building operations to improve energy efficiency and building performance. Although more widely used for new building energy performance simulation and prediction, there are also opportunities for energy modeling in retrofit projects.

Energy modeling provides accurate modeling of the real-time conditions and the existing building system energy performance evaluation. Various tools are used for energy modeling, the Department of Energy identifies over 300 on their Building Energy Software Tools Directory (DOE 2013), including Energy Plus, eQuest, Trane Trace 700 and Hourly Analysis Program (HAP) being among the most common in industry (Coulter et al, 2013). The relationship of energy audits and energy modeling from the perspective of information exchange is shown in Figure 22, suggesting that a standard data format among the tools shown would offer greater flexibility in the re-use of collected data later in the process, and may facilitate greater investment in the initial stages through reduced cost of assessment in design.

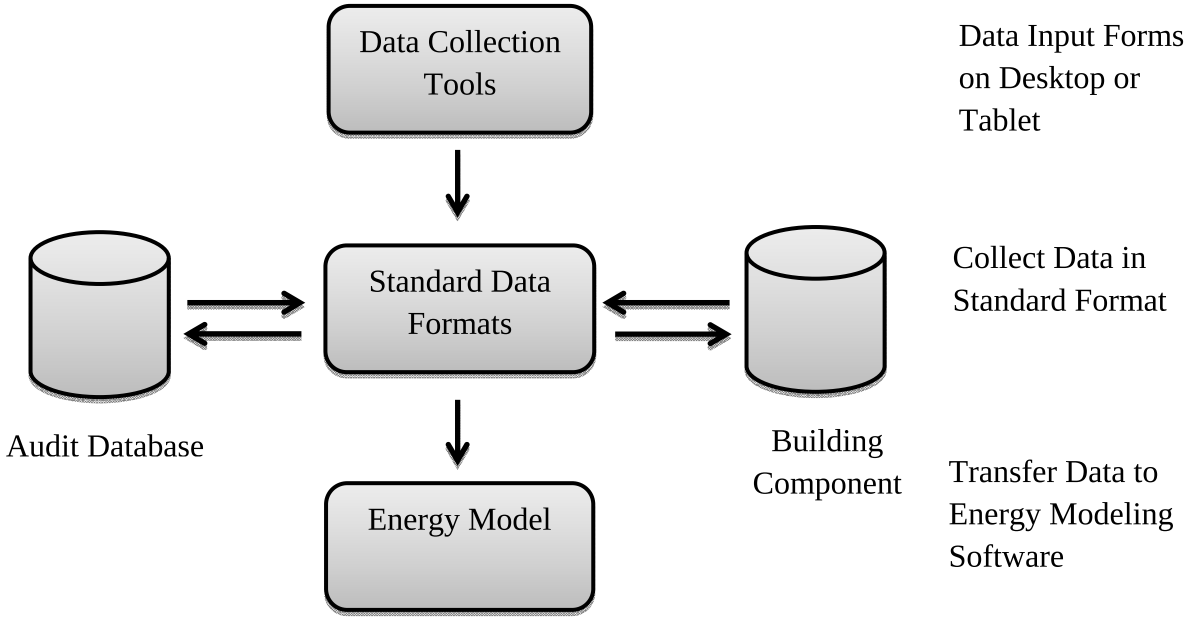


Figure 22: Data Flow between Energy Audit and Energy Modeling

3.2.3 Content analysis Method and Workflow

In order to integrate the energy audit and energy modeling information exchange requirements, the currently available energy data structures were analyzed and the relationships between these data structures were identified. The content analysis scope is shown in Table 1. For the energy audit templates, detailed data items were extracted from all sample forms and organized according to building construction systems. Energy modeling input data was extracted manually from the software data entries. The detailed data items under each data structure were cross compared, including the data description, data type and unit. Based on the analysis, the differing details by tool were addressed in order to extract the energy audit characteristics. The workflow of the analysis is shown in Figure 23. The standardized data input of these energy modeling tools was analyzed in order to compare the data from the energy audit standards in order to establish the link between the energy audit and energy simulation process.

Based on the workflow, the data item details from each available data structures were extracted from the template forms or software database and inputted into spreadsheets. Each item was cross compared to identify the overlaps and gaps between different data structures. Currently, The ASHRAE Procedures for Commercial Building Energy Audits is the only industry standard that provides guidelines for building energy audits in commercial building retrofits sector, which is comprehensive to cover the core data of different levels of energy audit. Therefore, the ASHRAE template forms were referenced as the baseline for the analysis. Each data item was analyzed based on data description, data type and unit and coded in spreadsheets. The data structures were cross compared against the ASHRAE standards based on the data item details. The overlapped data were marked and aggregated to calculate the percentage of data alignment.

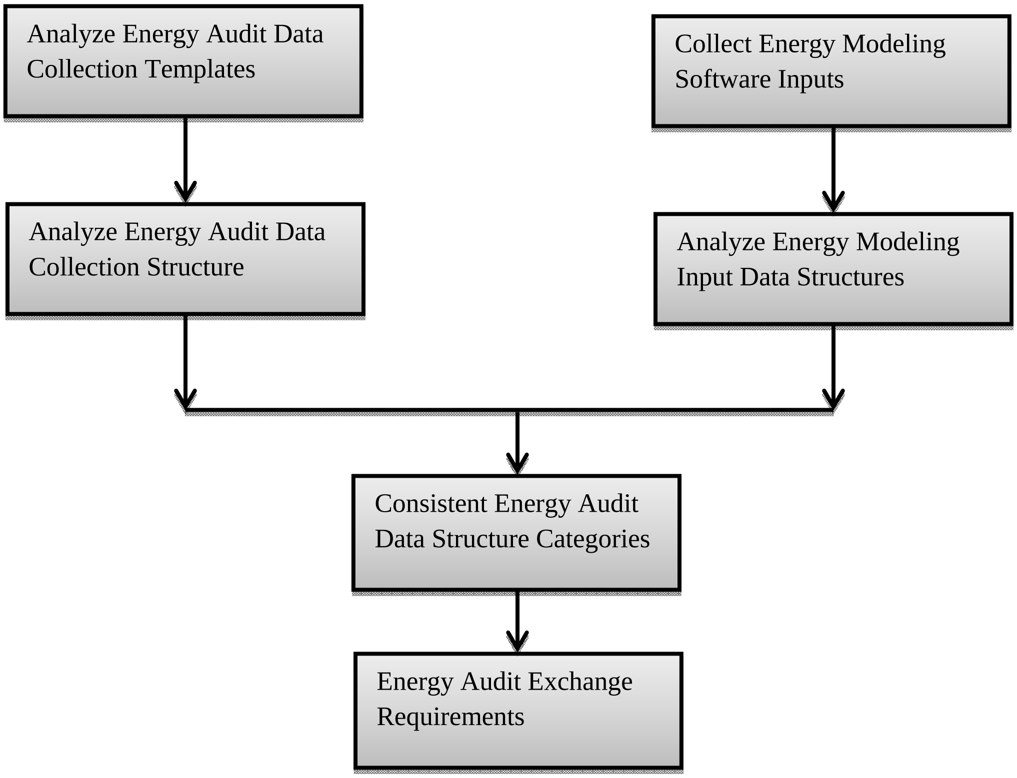


Figure 23: Content Analysis Work Flow

An example of the comparing details is shown in Table 2. In this example, the ASHRAE template forms contains 12 data items on building envelope systems as the table shows, the item ID was coded through the template forms categorization. The data type and unit was analyzed to facilitate the comparison. The RMI data items in the building envelope category were compared against the ASHRAE data items. If the data item description conveyed identical information, the item was marked as an overlapped data. For some data items, the descriptions were slightly different in terms of level of detail. For example in the ASHRAE template, the insulation information was recorded by identifying whether the building system has an insulation layer or not (data item 2.4.2, 2.4.6. 2.3.8), which was a very rough description, however, for RMI templates, the insulation information was recorded by both insulation type and thickness. In such cases, the data items were marked as overlapped information despite of the differences in characterization. The overlapped items were summarized by each category, in this example, ASHRAE and RMI had 6 overlapped data items out of 12 total items. Therefore, the data alignment would be 50%.

Based on the statistical analysis, the percentage of data alignment is summarized as shown in Table 3 and Figure 24. The core data were categorized into eight groups which are covered by all of the energy audit tools as shown in Table 3 and Figure 3. Historical building energy use data in ASHRAE template forms are excluded from the analysis, as this category of information is not covered by most energy modeling software.

Table 3. Energy Data Alignment Summary

Category	Energy Auditing				Energy Modeling							
	ASHRAE		RMI		eQuest		Energy Plus		HAP		Trace 700	
	Items	Alignment	Items	Alignment	Items	Alignment	Items	Alignment	Items	Algnment	Items	Alignment
General Information	32	100%	11	**34%**	10	**31%**	9	**28%**	11	**34%**	6	**19%**
Utility	40	100%	23	**58%**	1	**3%**	3	**8%**	0	**0%**	2	**5%**
Schedules	5	100%	2	**40%**	2	**40%**	3	**60%**	3	**60%**	0	**0%**
Building Envelope	12	100%	6	**50%**	5	**42%**	9	**75%**	8	**67%**	4	**33%**
Lighting System	11	100%	7	**64%**	0	**0%**	2	**18%**	3	**27%**	0	**0%**
HVAC System	27	100%	10	**37%**	13	**48%**	14	**52%**	10	**37%**	11	**41%**
Domestic Hot Water	7	100%	4	**57%**	3	**43%**	4	**57%**	0	**0%**	0	**0%**
Special Loads & Other Systems	10	100%	3	**30%**	0	**0%**	0	**0%**	5	**50%**	0	**0%**
Total	144		66	**46%**	34	**24%**	44	**31%**	40	**28%**	23	**16%**

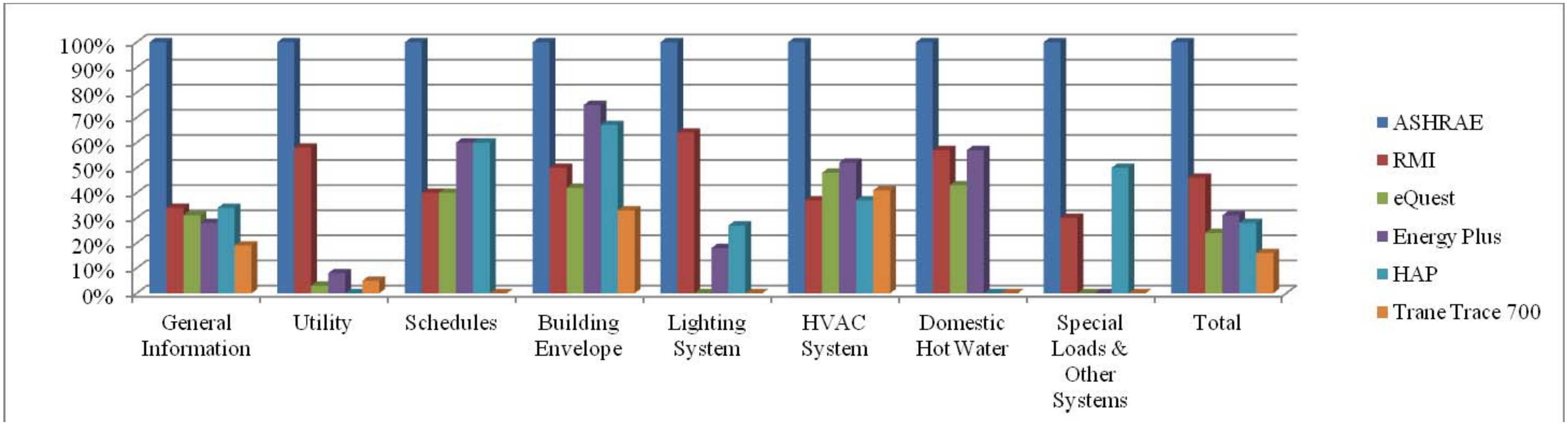


Figure 24: Energy Data Alignment Summary

3.2.4 Standard Audit Exchange Conclusions

Data collection of existing building conditions is significant to the detailed energy and economic analysis of energy retrofit projects. Identifying the information exchange requirements of energy audits offers potential to improve information flow from energy auditing to energy modeling processes by reducing the work of manual data entry. Mistaken data and re-collection should also be reduced. Furthermore, information exchange requirements help to define the standardized process. However, there is no information exchange standard for energy audits and little research has been focused on energy audits in terms of information exchange requirements.

This section described the variability in energy data characterization between energy audit and energy modeling by analyzing the currently available energy audit template forms and energy modeling software input data for four common energy modeling applications.

Based on the analysis results, the overall alignment of the data structure among current energy audit templates and energy modeling tools is low. The average alignment of the energy modeling inputs with ASHRAE template forms is 24.5%. Two identified reasons contribute to the phenomenon:

> 1) Most energy modeling tools are designed to simulate and predict the energy use of new buildings rather than existing buildings, thus there several data input categories, such as utility bills, which are not standard inputs for energy performance modeling tools;
>
> 2) The ASHRAE template forms are designed for both owners/facility managers and professional to understand the procedures of energy audit while most energy modeling software are designed for professionals only.

ASHRAE identifies qualitative information for some system and equipment evaluation while most of the input information for energy modeling software tools is quantitative. Moreover, while most energy modeling software recognizes the HVAC system and control as the most important part of energy analysis, lighting system and plug loads are not the focus for most of the energy modeling tools.

Despite the different foci, it is essential to leverage the audit data for detailed energy analysis. The identified overlaps and gaps should be analyzed in order to improve the detailed information flow from data collection work in energy audit. Another benefit from analyzing the information exchange requirements of energy audit is to facilitate the field data collection process.

For example, both ASHRAE and RMI are considering the R-value as of the building envelope system as an important index in energy audit. However, it is difficult to identify the R-value of the building system during data collection. While the energy modeling tools are using dimensions and materials, the R-value could be automatically calculated and provided. Analyzing the differences is helpful to identify the energy audit characteristics in order to facilitate the data collection process.

3.3 Uncertainty Quantification Advancements and Results

UTRC made advances in three fronts: interface of an uncertainty quantification and sensitivity analysis (UQSA) module development, development of an xml interface to integrate with the iPad data output, and integration of an economic module. Both are described in what follows. IBM also made advances in developing a statistical procedures for estimating uncertainty of the thermal parameters of building envelope recovered from the inverse modeling.

Uncertainty Quantification and Sensitivity Analysis for Parameter Calibration

UTRC integrated an uncertainty and sensitivity analysis into the DeepRetro analysis of a building (e.g. selection of internal systems). As an outcome, methods have been developed for model-based optimization and model calibration that consider thousands of partially known model parameters.

In the optimization work, cost functions can be defined to obtain a number of different objectives, as desired. In model calibration, we define the objective to target the error between the prediction of the model and data captured from sensors in a real building. An optimization is then performed to identify parameter combinations that drive this error to a minimum which results in the model output aligning with the sensor data. This approach to input parameter calibration has been applied in all 8 Navy Yard building use cases.

Application of Uncertainty Quantification to Simulation Calibration

The Uncertainty Quantification and Sensitivity Analysis (UQSA) routine was used to calculate the sensitivity of the energy use to the input and assumed model parameters. This is the longest part of the calculations, taking up to two days. Following the uncertainty quantification, a calibration routine uses the UQSA results to fit adjustable parameters to match the measured utility data. Therefore the buildings without utility data could not be calibrated. The calibration routine takes only minutes. When the calculation with uncalibrated default values was within 20-30% of the measured value, the calibrated result would fall to within a few percent of the measured value. If the default calculation was greater than 10-30%, the calibration routine could not adequately adjust the parameters to fit the experimental data.

The calibration routine outputs a graph, similar to the uncalibrated solution demonstrating the improved accuracy in **Error! Reference source not found.**. For building 101, after input calibration was performed, the total energy prediction was matched within 5% error (20% before calibration, as shown below).

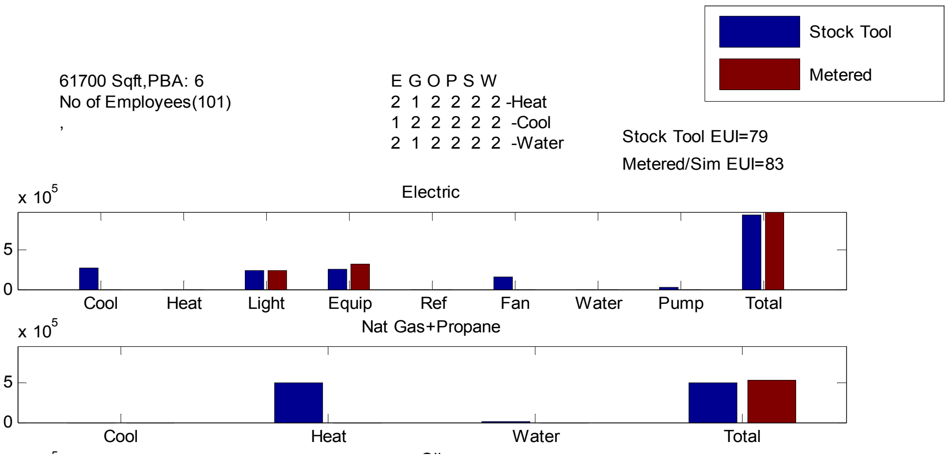


Figure 24: Results for building 101 after calibration

The tool also outputs a graphic, see **Error! Reference source not found.**, comparing the measured, uncalibrated, and calibrated results. **Error! Reference source not found.** shows a breakdown of the Building 101 metered and simulated performance using the DeepRetro engine compared to the metered data. The errors with and without calibration (bottom right), and the parameters varied (left hand list). The numbers next to the varied parameters are the factors by which the default values are multiplied to reach the calibrated results.

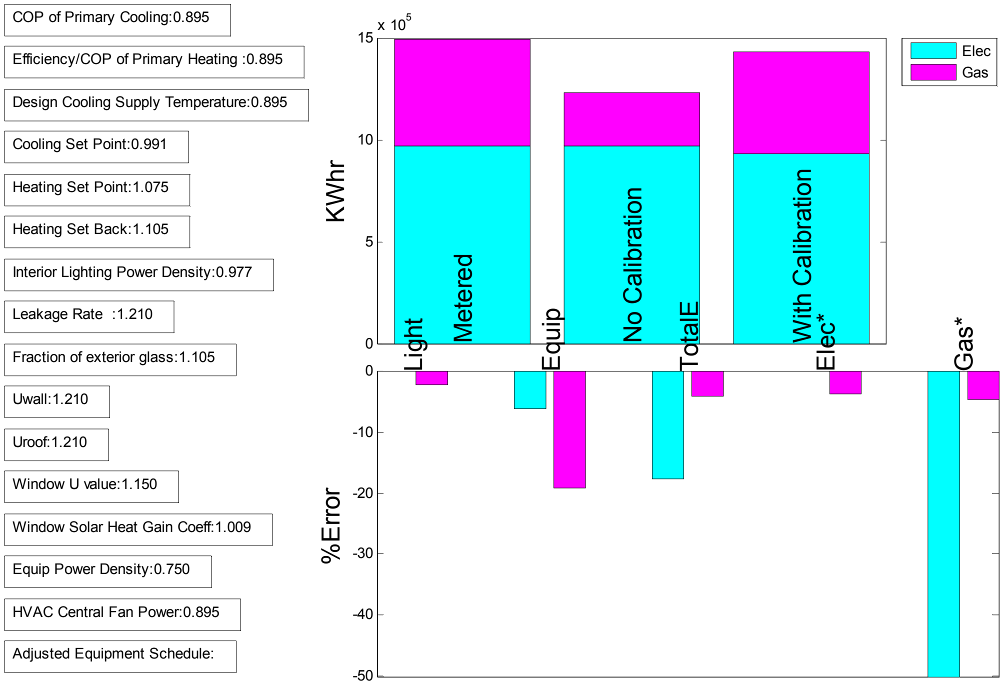

COP of Primary Cooling:0.895
Efficiency/COP of Primary Heating :0.895
Design Cooling Supply Temperature:0.895
Cooling Set Point:0.991
Heating Set Point:1.075
Heating Set Back:1.105
Interior Lighting Power Density:0.977
Leakage Rate :1.210
Fraction of exterior glass:1.105
Uwall:1.210
Uroof:1.210
Window U value:1.150
Window Solar Heat Gain Coeff:1.009
Equip Power Density:0.750
HVAC Central Fan Power:0.895
Adjusted Equipment Schedule:

Figure 25: Graphical output of building 101 calibration results

The total number of times that a particular value was adjusted during calibration of the eight Navy Yard buildings is shown in Figure 26. A weighted average, Figure 27, of the adjusted values is calculated by multiplying the absolute value of the difference from one for each adjusted value, summing across the buildings, and dividing by the number of times that value was adjusted, as shown in Figure 26:

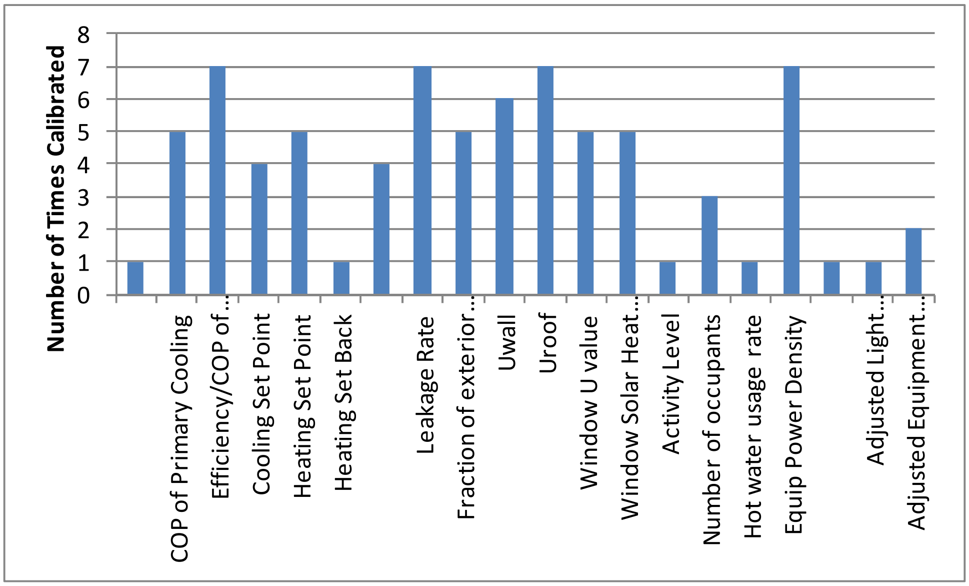


Figure 26: Number of times each parameter was varied during calibration for the 8 buildings

By observing which factors are adjusted most frequently and by the largest values, it can be seen that the primary factors needing better estimation are leakage rate, wall thermal resistance, roof thermal resistance, and equipment power density. This is not unexpected because these are the primary factors determining the energy balance of buildings. In addition, the COP/efficiency of the cooling and heating equipment is a significant factor.

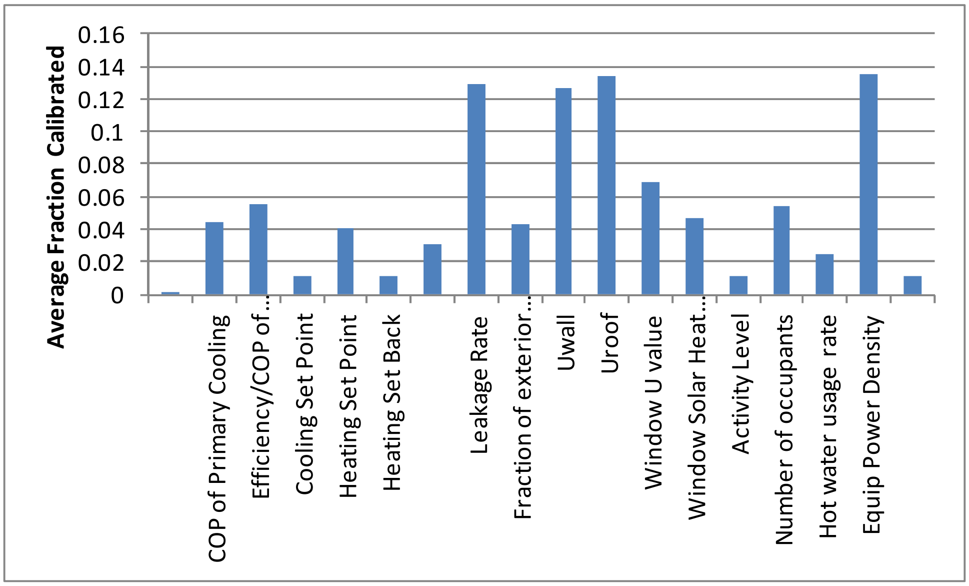


Figure 27: Weighted average of the percentage variation in each parameter during calibration of the 8 buildings.

Because the heating and cooling set-points were frequently adjusted by the calibration routine and setting proper space set-points was frequently chosen as an ECM, it is necessary to accurately record the current building nominal set-points during the field data collection process.

Uncertainty Quantification of Envelope Thermal Parameters

The thermal parameters for building envelope such as R-values and U-values of wall, window and roof etc., recovered have uncertainties. An integrated quantification method for computing the uncertainties and was developed by IBM team. The inverse modeling technique includes segmenting buildings into clusters based on similarities. The uncertainty quantification method utilized the time-series data of energy consumption as well as the information from similar buildings of the same cluster. The results are more reliable than the case where data from single building is used since the data from a single building may be limited. The equations and procedures for computing the certainty in terms of standard deviation and certainty bounds for each envelope thermal parameters are shown in the earlier section 2.2.

3.4 Inverse Modeling Advancements

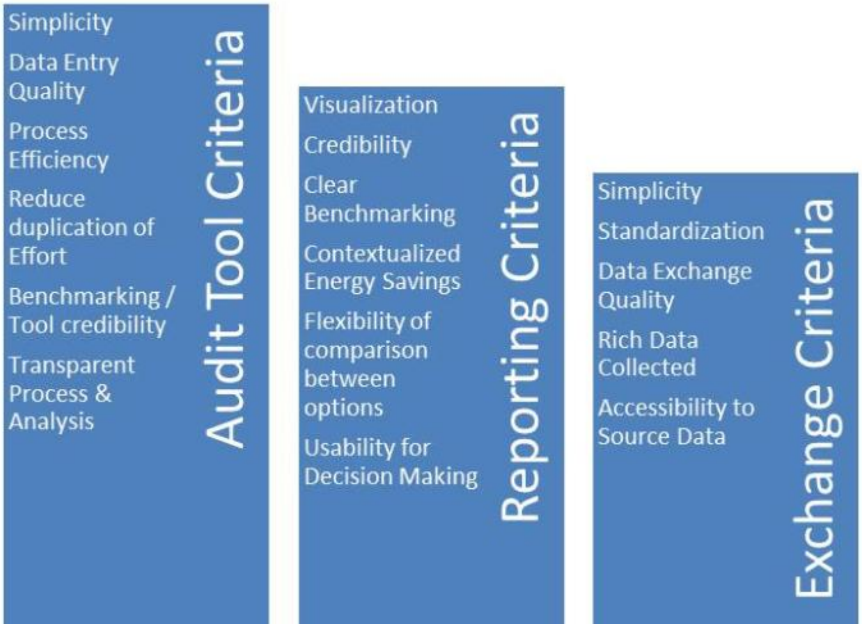
In the inverse modeling development, a data-driven approach was employed and estimate effective physical properties by correlating temporal data (monthly utility data) with weather seasonality and by extracting values from multiple buildings with similarities identified by the clustering algorithm. Building physical properties are discovered from tangible building characteristics and measurable data, not calculated from assumptions. These recovered effective values reflect a building's current status due to aging and degrading, and can be used in energy simulation and forecast in the corresponding forward model. The sensitivity analysis based on such a model can quantify energy/cost saving related to building envelop improvement and provide reliable benefit estimation for envelope retrofitting activities (ECMs). The inverse model also provides uncertainty quantification from statistical analysis (see section 2.2). The model is deployed via the cloud and well-integrated with cloud database. As a result, the tool can easily interact with other analytic tools.

3.5 Data collection application

Having defined the process and the data collection and analysis procedures, the development of the data collection interface was developed to follow, not lead the analysis as a developmental step. While the field data collection procedure takes please before the analysis, using the DeepRetro tool, the tool data collection is intended to align with the data collection needs of the tool. Following the process workshop, shown in Figure 28, the feedback from the workshop participants regarding information flow and challenges was used to identify traits to target for the interface development.

Figure 28: Images of industry members at audit process workshop.

The workshop generated criteria related to three categories: 1) attributes of the audit tool or application; 2) reporting criteria from the process; and, 3) data exchange criteria. The summarized criteria, shown in Figure 29, were used as the baseline for defining the features of the iPad application and interface development.



Audit Tool Criteria
- Simplicity
- Data Entry Quality
- Process Efficiency
- Reduce duplication of Effort
- Benchmarking / Tool credibility
- Transparent Process & Analysis

Reporting Criteria
- Visualization
- Credibility
- Clear Benchmarking
- Contextualized Energy Savings
- Flexibility of comparison between options
- Usability for Decision Making

Exchange Criteria
- Simplicity
- Standardization
- Data Exchange Quality
- Rich Data Collected
- Accessibility to Source Data

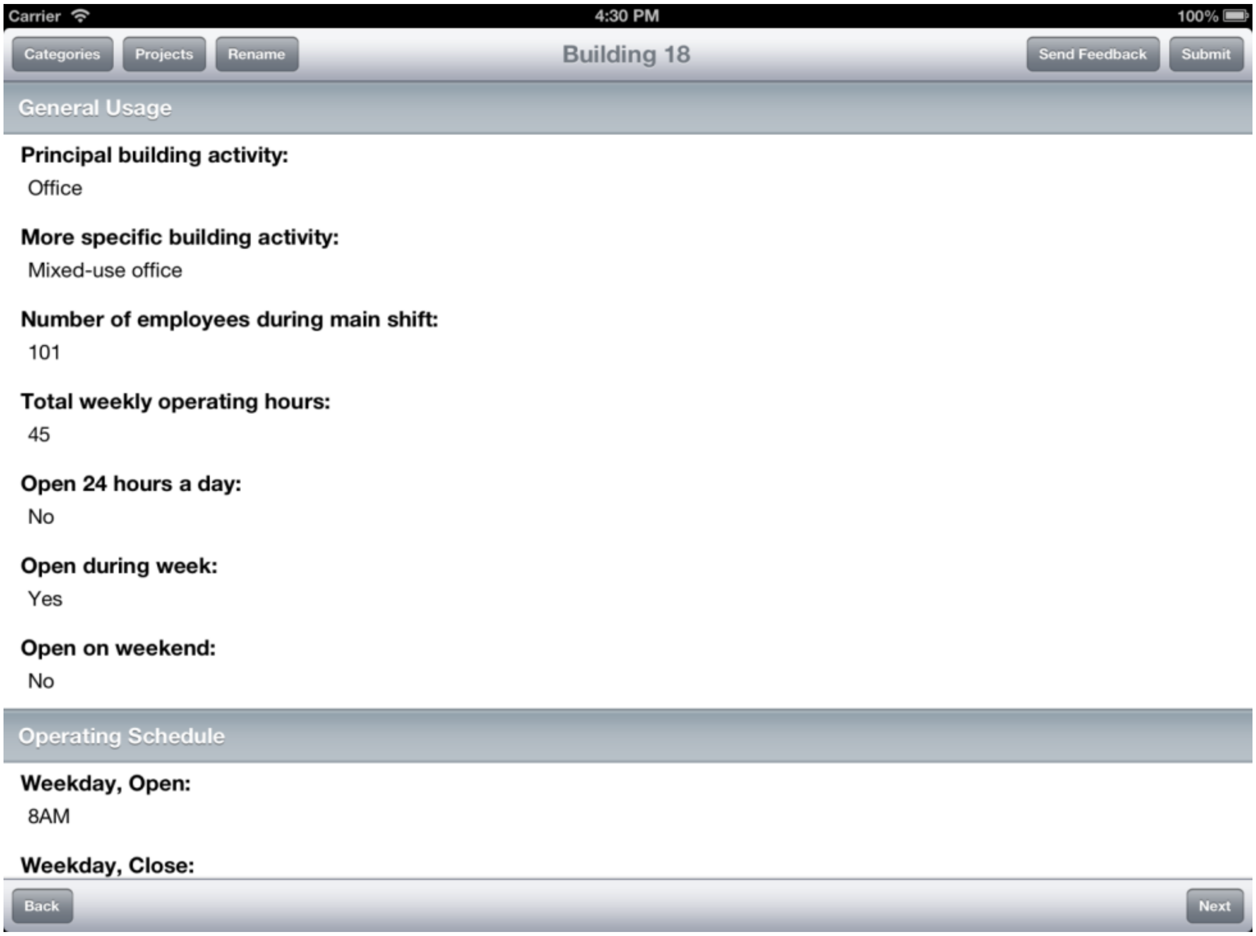
Figure 29: Summarized Audit Tool and Process Criteria from Process Workshop

The iPad Application was design with three goals:

1) Modularity to allow for downstream modification to support the Design Tools Platform and data requirements;
2) Simplicity to allow the user to focus on the data collection needs, but enable opportunities for them to capture rich data; and,
3) Quality of data entry through simple interactions with appropriate detail for the data entry.

With regards to the modularity, all content for the Energy Audit application is read in from "plist" files, which are simply XML files with a specific set of data descriptors. "Content" includes questions, potential answers, descriptions, and rules for processing input. The app is aware of all the plist files and their "version," which allows for easy updating of the content to take place by downloading new plist files from a server if future updates to the tool are generated. Essentially, the questions, answers, order of questions, and all other data fields, are all determined from the plist files which are easily updated. In addition, the separate data entry pages are separated as modules aligned to the plist to allow for quick adjustments to the set of interfaces.

To address the simplicity and quality directives, the interface is developed to maintain a simple set of data entry items, with a sample screenshot shown in Figure 30.



General Usage

Principal building activity:
Office

More specific building activity:
Mixed-use office

Number of employees during main shift:
101

Total weekly operating hours:
45

Open 24 hours a day:
No

Open during week:
Yes

Open on weekend:
No

Operating Schedule

Weekday, Open:
8AM

Weekday, Close:

Figure 30: Screen shot of Audit application - building usage data

XML interface

The DeepRetro tool is provided in MATLAB executable form and the inputs are collected in Excel files. The iPad interface provides XML files on a web location. The tool is able to directly download the XML files and translate them into the current Excel format.

Due to the focus of developing the new interaction for an iPad, and since the iPad does not support MATLAB, the file exchange from the data collection to the analysis is performed through XML format.

The current DeepRetro tool uses input from Excel files as the data entry from the field assessment. The input is pre-processed in Excel to align the input variables with the analysis.

For this purpose, a MATLAB based translator has been created. The translator matches names of the input categories between Excel and XML and writes the XML inputs into corresponding place in the Excel input template (template comes with preprocessing algorithms). The preprocessing is still done in the Excel file. The DeepRetro core engine does not have to be changed for this purpose because it still communicates with Excel only. The modular design of the application allows for simple updates to the XML exchange in parallel with any needed interface updates.

4.0 Costing and Economics of Energy Conservation Measures

4.1 Cost integration development with modeling tools

To perform economic viability analysis, energy outputs from the DeepRetro tool are translated into economic terms. To accomplish this, an additional module has been added to the DeepRetro tool. The economic analysis relies on the output of the energy analysis and additional economic parameters. A new addition to the current interface has been developed. This interface gathers data related to utility costs, capital costs, inflation rates, discount rates, incentives, system life, and other optional parameters or traits.

Methodology

The information flow for the economic analysis is shown in Figure 31.

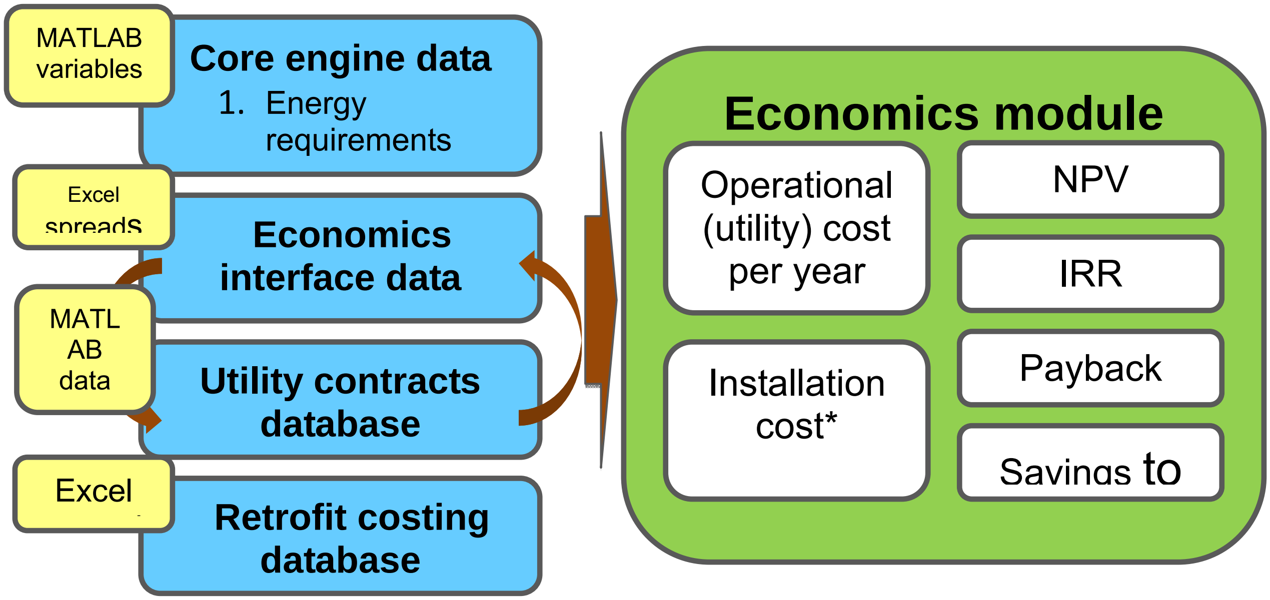


Figure 31: Information flow for economic analysis

The economic module calculates time series of utility costs based on the time series of energy usage coming from the energy module. The calculation can be based on averaged utility cost per kWh or could be defined via specifying detailed contracts with utility companies in terms of peak, part peak and off peak hours and associated energy and demand cost by seasons. Utility cost data and descriptions are additional inputs to the tool and will in future be a part of the database. Time series of utility costs are calculated for both baseline and retrofit solution which are then used to calculate the savings per year.

The installed cost of ECMs is an additional input to the tool which can be defined in two ways. One way is to input the cost in absolute value in dollars for each implemented ECM if a known detailed cost is budgeted. Another way it to express the cost per ECM as a function of building specific information inherited from the energy module. The current costing input is defined in the following section. We are considering including additional factors that would be based on additional user inputs (e.g. specifying whether the work will be performed from inside or outside, during occupied building or not) that will be used to derive factors for cost multiplication. Due to uncertainty and variability of initial installed costs of ECMs inputs, we are also considering adding an uncertainty in economic predictions.

Based on the utility cost, installation cost and inputs that define utility inflation rate, discount rate, incentives, life time of equipment, the module will calculate net present value, internal rate of return, payback period (simple and compound) and saving to investment ratio. The calculation of these quantities has been validated against dedicated Excel-based calculations. The calculation of these quantities has been verified against dedicated Excel-based calculations.

The building input data file that contains description of the building current state. The level of the required inputs is mostly descriptive and easily filled-in during the audit process. Input parameters that are not available are defaulted. Input files have been enhanced with input data immediate validation. The data validation provides information to the user about necessity of the data. The distinction between mandatory and optional inputs has been made explicit in colors and in comments. The next generation of the input files will inherit all the developments from the current one and will be more interactive.

The Packages input file contains a list of ECMs that could be bundled into a single solution. The inputs are only switches that activate ECMs

The Schedules input file contains information about occupancy and lighting schedule (optional input). It requires hourly input in percentages for schedules and makes distinction between week days and weekend schedules.

The Economics input file contains relevant inputs for economic analysis. This is the most recent addition to the inputs. The file requires general information about the interest rates, discount rates, incentives, life of equipment being installed and provides different level for inputs for utility and installation costs. Utility cost can be provided by the average price per kWh (suggested price per State is given based on the latest available information published on www.eia.gov) or detailed utility contracts could be modeled. Costing data could be provided per ECM or more generic by defining an equation based on the available building specific parameters obtained from energy simulation. The costing database will be developed in BP3.

The output of the tool is currently in Excel format. The energy output is given by energy source type and use type in kWh and in percentages savings for each packaged solution. Both annually and monthly outputs are available.

The economics output provide economic metrics: NPV, IRR, savings to investment ratio, payback in years and annual and monthly cost per source energy type for each packaged solution.

The emissions output is provided in tons of CO2 per year.

Illustrative results

The buildings were modeled with default values, without using UTRC calibration model, for parameters such as the wall UA. The results of the calculation are output in graphical format **Error! Reference source not found.**.

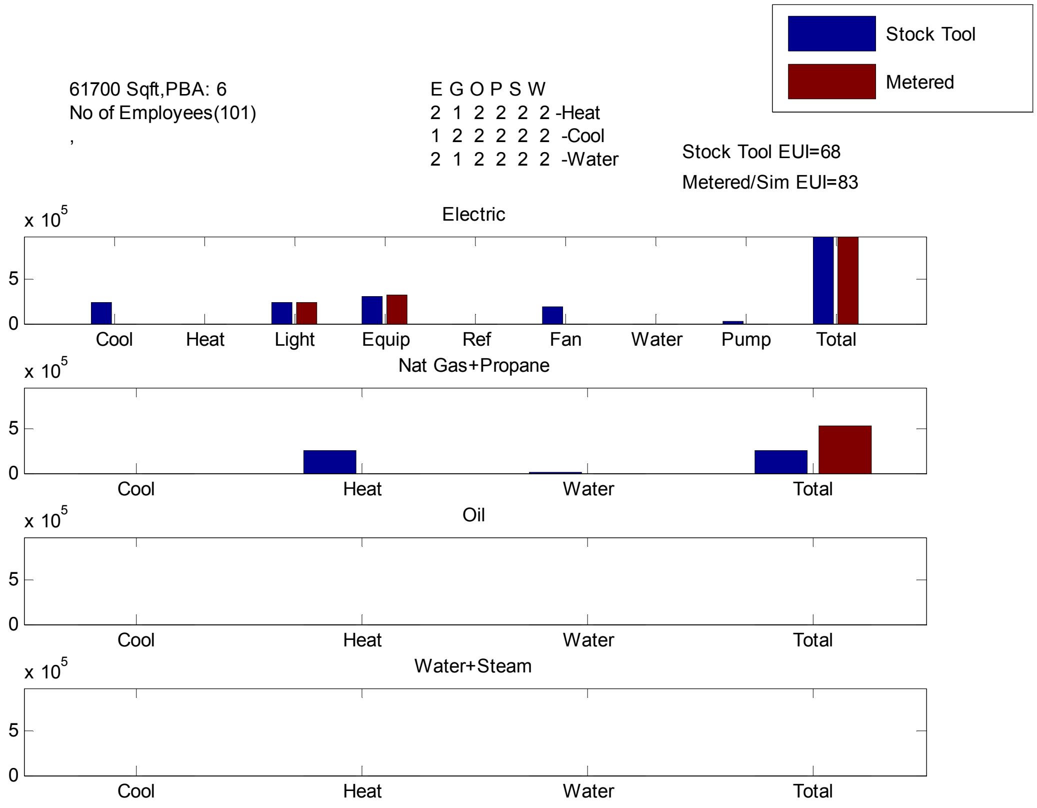


Figure 32: Simulation results for Building 101 before applying UQ for parameter calibration (i.e. uncalibrated results)

The economic module has been integrated into retrofit analysis and used for a set of Navy Yard buildings. Sample results show energy savings for different retrofit packages and associated payback period are shown in Figure 33 and Figure 34.

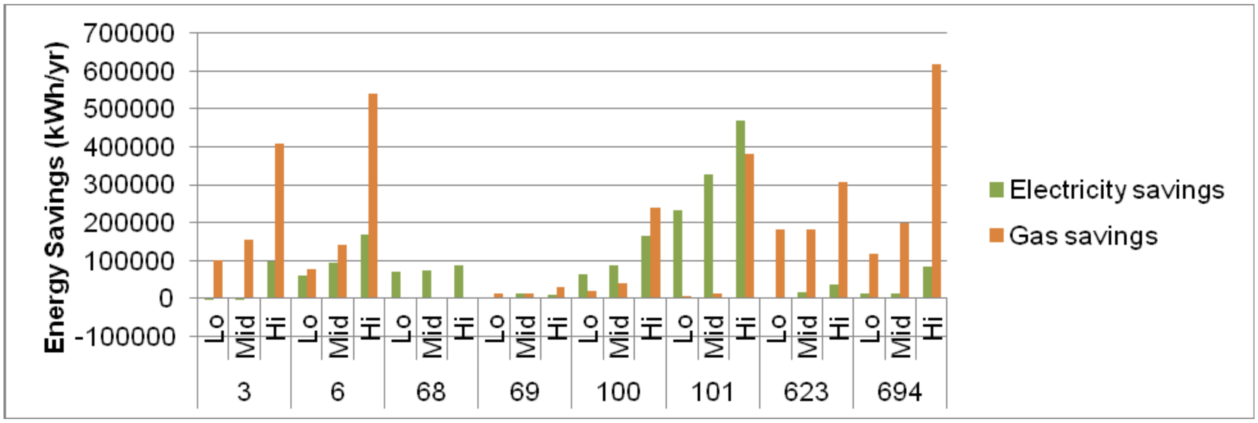


Figure 33: Energy savings for set of Navy Yard buildings and different retrofit packages

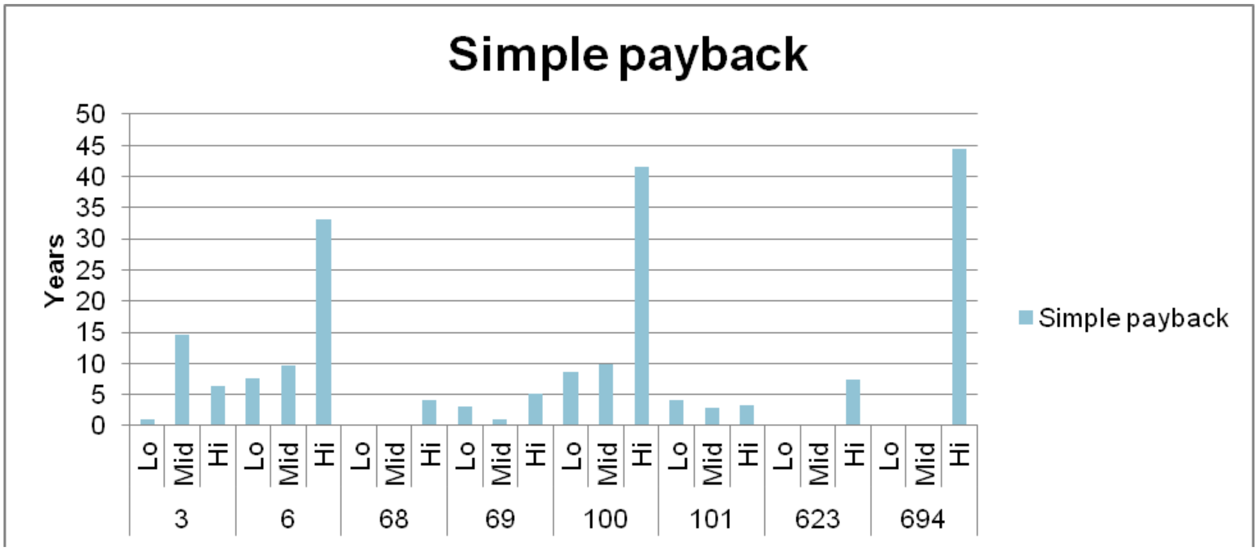


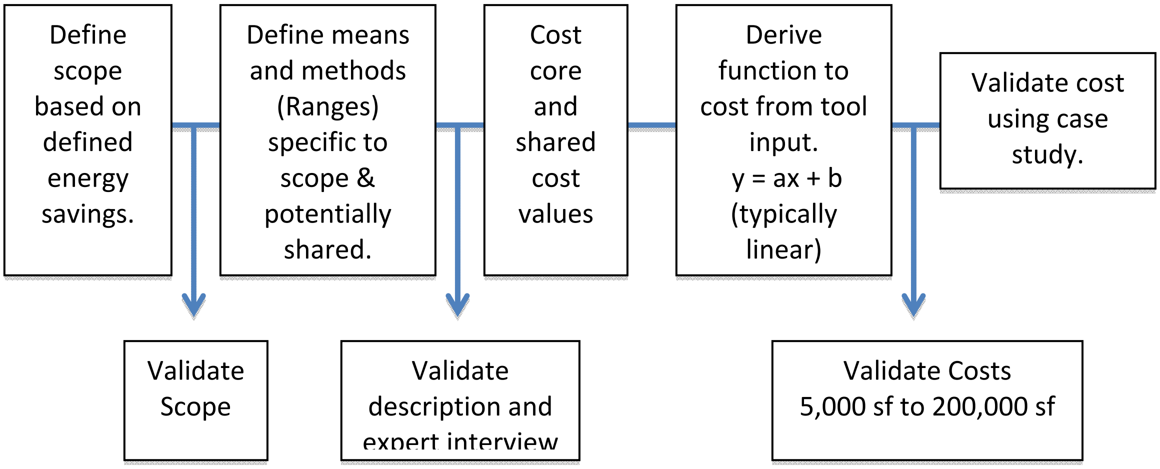
Figure 34: Simple payback calculated for different retrofit packages applied to the set of Navy Yard buildings

The figures show that even though the energy saving potential could be significant, the cost of the retrofit package will determine its applicability to the site.

4.2 Costing methodology of ECM's

The evaluation of energy conservation measure costs is a component in a larger research project to develop a Level I Energy Audit tool. The Energy Audit tool is targeted to produce rapid and reliable energy conservation measure evaluations to more thoroughly identify integrated retrofit opportunities. The goal of this analysis is to define the methodology and develop the energy conservation measure cost data to support the initial construction cost development for evaluation in conjunction with a Level I Energy Audit, within 10% accuracy for the system costs. The core focus of the study is to develop cost measures which align with the audit data collection methodology for building parameters, such as square footage or air supply flow rate. This information will be imbedded into a feasibility tool that will have the capabilities to reflect costs for individual ECMs as well as ECM packages. Future steps will be performed to study and align packaging ECM costs to allow building owner's the opportunity to analyze different scenarios based on goals and expectations, which can potentially reduce the overall risk to ECM implementation.

4.2.1 Research Methodology



The research methodology requires the gathering of quantified data from relevant costing sources and qualitative data from interviewing industry experts to define reliable costing process and feasibility metrics for energy conservation measures. The goal is present energy conservation measure unit prices in a uniform format allowing the data to be easily integrated into the costing tool. Few data metrics for the energy conservation measures will be used which will allow minimal building parameter inputs to be required, thus allowing a rapid feasibility analysis.

4.2.2 Core cost development

Forty-one energy conservation measures have been identified for used in the energy audit tool, with descriptions for each included in Appendix B. Development of the cost for each ECM relied heavily on defining the construction scope. The construction scope is directly related to how the energy conservation measure was defined in the energy audit tool. Aligning these two pieces is essential to capture a reliable snapshot for ECM costing. Categorizing the implementation level for each ECM was instrumental in defining the magnitude of each scope. Establishing levels of System, Sub-system, and component scopes and costs directly correlated with the scope levels. Direct and indirect construction activities were identified during the development of the ECM construction scoping. It was also important in identifying the trade that is required to perform the installation each ECM. Once all scope related questions were answered, cost association was performed accordingly using RS Means Cost data.

In order to establish consistency, hypothetical building parameters were integrated into cost development. A 100,000 SF, 5-Story building was the basis of ECM analysis for the initial cost development. This allows for ECM unit prices to be represented as a square foot cost, allowing consistent unit measurements. Where square foot unit measurements do not represent the most reliable approach to costing a particular ECM, unit prices are defined based on system analysis output from the DeepRetro analysis. For example, if a variable air volume system was being analyzed, the air flow in CFM is one output that can be leveraged to more accurately size the system in comparison to the collected building information, whereas a gross area calculation would be based on an assumed air flow rather than the simulated. Approaching costing with unit measurement consistency in mind, limited-building parameters will be required when using the energy audit tool. Applying the building parameters to a defined construction scopes for each ECM, the unit prices can be calculated. Each ECM was analyzed independently and associated costs were included.

These costs were then aggregated into Assemblies Based Estimating to allow for rapid analysis of the building construction scopes as assemblies, rather than detailed cost breakdown by component, based on the defined assembly considerations needed to achieve the simulated energy savings.

4.3 Costing Individual ECM Approach

When creating the assembly based costs, three types were identified: gross building, system specific-simple, and system specific – stepped:

Gross building – ECM scopes which were aligned with the building square footage, such as changes to the building's lighting system are quantified based on the assembly cost per square foot of building area.

System Specific-Simple: ECM scopes which have more accurate system costs based on the captured building information from the walk through assessment were quantified using the system specific area, or similar sizing parameter such as the CFM airflow noted previously:

System size (eg. Area) x [Demolition Cost + Design cost + Building Cost for New System]

System Specific-Stepped: Within certain ECM scopes, they could be typically costs similarly to the system specific-simple costs, with the exception that at certain scales the base fixed costs jump. For example, the controls systems would typically scale with the size of the system, except that the systems are size to align with a scale of control points, when the control points exceed set numbers the infrastructure, such as the panel and router costs, jump in scales not directly aligned with system sizing.

[SF Area x Additional Costs] + [Core Cost x Complexity Points]

4.4 Cost Innovation Workshop & Outcomes

The workshop was designed to (1) review the current energy conservation measures employed in the energy audit tool and (2) capture opportunities and links for novel ECM pairings likely to enable opportunistic cost or energy reductions. Bringing together roughly 30 industry experts in different design and implementation aspects of energy reduction, the discussions centered on better clarifying the value and benefits certain measures pose to owners and the perceptions of complexity associated with the individual and grouped measures. Using these discussion points, the groups generated outcome metrics based on their clustered themes, such as energy use/person, reduced system stress (net kwh consumption, w/sf target), energy benchmarking (building in current state and compared to other regional buildings), economic value (LCC, ROI, Maintenance Costs) , and EUI Savings. After sharing their metrics and interpretations of value and complexity, the groups revisited their discussions of ECM's to identify strategies for grouping the measures to target increased value and reduced complexity for improving the rate of adoption of Energy Measures.

4.4.1 Introduction

The Research Team summarized the background of the EEB Hub organization and the Building 661 demonstration project. Bevan Mace, from Balfour Beatty, then introduced several example case study retrofit projects where the project team was able to achieve substantial energy savings with novel solutions or targeting systems which were initially written off due to poor return on investment.

Goal of the workshop: Define Innovation Strategies for Retrofits with advanced energy goals.

Expected outcome: A suite of empirical guides will be created to support successful owner practices regarding roles, team integration, and team behavior, delivery methods, procurement methods and project performance.

Objectives:

- Employ a cross functional team approach to energy problems in retrofit projects
- Discuss metrics for improving alignment of value for complexity in retrofit project
- Develop strategies for improving ECM approaches and business case for retrofit and energy projects

4.4.2 Clusters

The workshop attendees were organized into 5 groups, each with typically 6 members. The groups, or clusters, were composed of cross-functional teams so all members had different backgrounds ranging from architecture, to mechanical engineering, to electrical specialty contractors.

The groups were assigned one of the following topics to facilitate and theme discussions:

- Space Utilization
- Load Reduction (passive systems)
- Optimizing Systems (integration)
- Renewables Integration

Mapping Energy Conservation Measure by Benefit and Complexity

After mapping the ECM's associated with their cluster, the teams were asked to define what they considered the ideal retrofit process and use that definition to generate metrics which would better align the goals of the ideal projects with measures specific to their clusters. The ideal process traits generally agreed to be:

- Set Expectations by Owner & clearly defined goals.
- Robust Baseline Data
- Team Approach/Buy-in (Owner, Arch, Engr, Contractor)
- Construction Conditions (Building Unoccupied during construction)
- Adequate Budget
- Educated Owner

While the details of the ideal process varied, the above items were fairly typical. Each cluster used that ideal process to generate a list of potential metrics to better align current project ECM scopes to meet the values and benefits embedded in this ideal process, here are the highlights of those metrics:

Space Utilization

- Cost Savings, Cost per person, Monthly Costs, /Maintenance/Repair Costs
- Percent Recyclability
- Quality – space to performance
- Energy use / person
- Level of Comfort: Ratio/Percent of Control of systems
- Percent Reuse (quality/quanity of waste)

Load Reduction

- Level of Energy Reduction goals (w/sf target)
- Percent of Air Distribution
- Benchmarking: w/sf by use type and region
- End User Productivity output: Sickness rate, employee retention)
- Reduced system stress
- Occupancy or % rental rate

Optimizing Systems

- Energy Savings: Baseline of existing building & similar regional buildings
- Economic Value: LCC, ROI, Simple Payment,
- Reliability of ECM: Likelihood implemented ECM being compromised by end user.
- Building Value: Pre-ECM vs Post-ECM

Renewable Integration

- Satisfied Occupants: Number of complaints (%)
- High Performance Asset: ECU Savings
- Positive Community Engagement: Impact on nearby buildings
- Costs: D, C & O costs
- Quality: Service Calls, CMMS

4.4.3 Workshop Outcomes

After the discussion of the ideal retrofit process and better metrics for capturing it, the clusters re-grouped with the goal of coming up with strategies for pairing or grouping energy conservations measures to increase the value captured in one scope.

Usage strategies (end user value)

- Hoteling
- Occupant satisfaction (daylight + Demand control vent)
- Civic – trees, green roof, EV charging
- Interior flexibility (underfloor air, modular partitions, open office)

Radical System strategies (energy value)

- Variable Refrigerant, size for higher density
- Split heating/cooling from fresh air
- DC / AC distribution split

System Groupings (1st cost value)

- Envelope groups
- Control / demand approaches
- Ceiling/plenum groups (hvac + lighting)

Every Project

- Controls upgrade, metering
- Scheduling
- M&V / Retro Commissioning
- Train O&M staff / align complexity of system to capabilities of team

4.4.4 ECM Analysis Results

The calibrated model was used to calculate the effect of individual energy conservation measures (ECM). The interaction between ECMs was not included in this calculation. The code creates a Pareto distribution of the energy savings with each package similar to Figure 35.

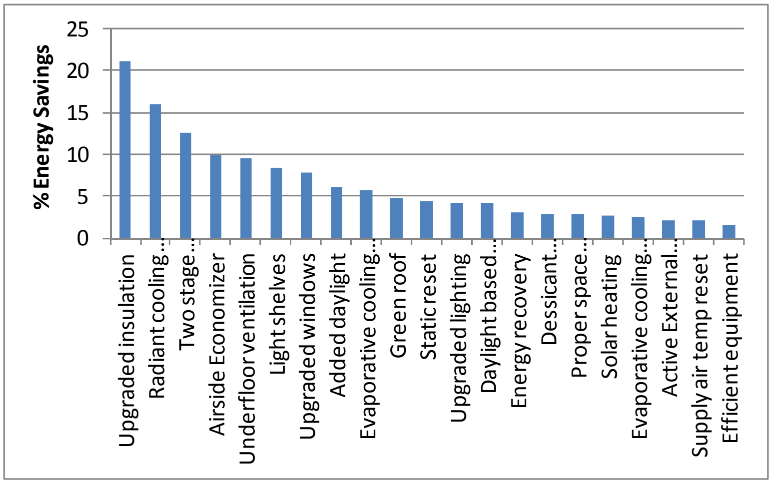


Figure 35: Pareto plot of energy savings with individual ECMs for building 101 for all ECMS exceeding 1% in savings

ECM Package Selection and Analysis

The ECMs selected for analysis in the Philadelphia Navy Yard Case Study buildings were grouped into low, medium, and high cost sets to demonstrate potential level of investment outcomes to present to a hypothetical owner:

- Basic/Low cost
    - Proper space setpoints
    - Weatherization
    - Heating plant optimization
    - Supply temperature reset
    - Daylight based dimming
    - Upgraded lighting
    - Static reset
    - Tankless water heating
- Moderate/ Medium cost
    - Solar heating
    - Condensing boiler
    - Airside economizer
- Major/High cost
    - Upgraded windows
    - Upgraded insulation
    - GSHP
    - Added daylight
    - Desiccant dehumidification
    - Green roof

The most effective measures in each level, as determined by the Pareto distribution, were assembled into packages. ECMs were selected that did not conflict with each other, for example, a condensing boiler and a ground source heat pump would not be installed at the same time. In future versions of the tool this selection will be automated to a greater extent, such as issuing warnings when conflicts are chosen.

As an example the following ECM packages were selected for building 101:

- Single ECM upgrades:
    - Upgraded lighting
    - Proper space setpoints
    - Supply temperature reset
    - Static reset
    - Daylight based dimming
- Moderate depth upgrades
    - Basic ECMs (All single ECM's as a package)
    - Airside economizer
- Deep retrofit upgrades
    - Moderate ECMs package (all single ECM's + Airside economizer)
    - Added daylight
    - Upgraded windows
    - Upgraded insulation

The total energy and economic savings with each package was then calculated. The interaction among ECMs is included at this point in the calculation. These packages lead to significant energy savings, as shown in Figure 36, of 17%, 23%, and 59% for the single, moderate, and deep packages.

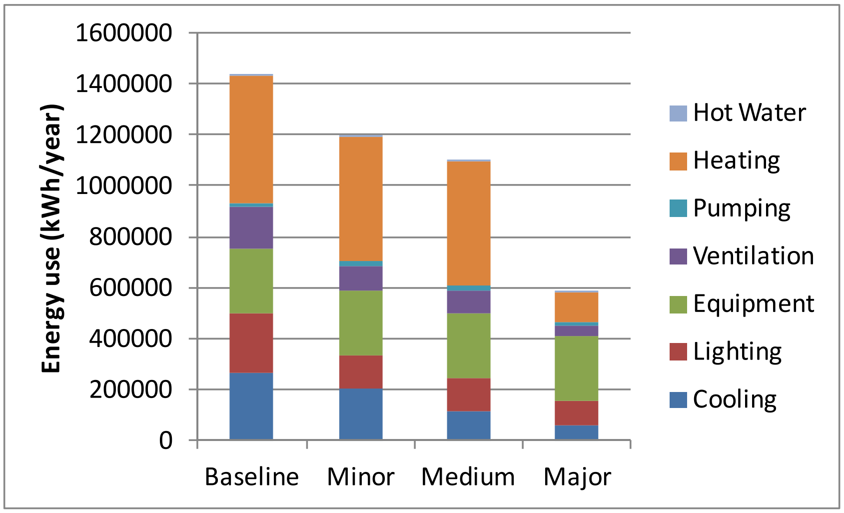


Figure 36: Energy usage as predicted with the baseline design and the selected ECM packages

An accurate calculation of the initial costs of many retrofit options requires detailed information about the building that is not included in the scope of a Level I energy audit. For instance, a green roof usually requires strengthening the roof structure to handle the additional weight of the plant growing medium. Determining the cost of this ECM needs information on the building structure that is not part of an energy audit. Because of this lack of information, the results of the economic analysis are heavily dependent on assumptions. Future versions of the code should give a high and a low estimate of the costs to bracket a realistic range.

4.5 Costing Methods Conclusions

The new module is a required element for every analysis, as shown in the process model, to inform the owner of the initial cost and financial planning implications. It provides the user with well known economic terms and support through financial detail in the decision making process for moving forward with a building retrofit.

The future steps for the economic module include:

1. Including uncertainty bars in the predictions of economic parameters.
2. Further feeding the costing database with validated data.
3. Expending options for building specific information (inherited from the energy module) in economic interface for generic ECM's costing definition.
4. Coupling utility costs to online database.

Conclusions

Based on the team’s experience with data collection for the Navy Yard buildings and the review of the independent audits of Building 101, the following conclusions were reached about ways to improve the Level I audit process and increase the level of confidence in the ECM recommendations for moving forward in the retrofit assessment and design process:

Despite using the same set of building data, multiple independent building energy auditors reached vastly different conclusions about the type of retrofits possible in a building and the potential energy savings of those retrofits. Some of this discrepancy may be due to the use of different and proprietary analysis platforms among the auditors, in addition to built-in predispositions to favor certain retrofits due to familiarity or other subjective factors. DeepRetro analyzes the same individual retrofit solutions for every building studied and rank orders them according to their predicted cost effectiveness alone. Energy saving packages can then be assembled from the individual components considering additional ground truth data about whether a particular retrofit is applicable to a particular building.

A systematic method is needed to gather and manage “ground truth” data about the building, whether through commercial software or through the iPad application. These tools should allow the data gathering process to be standardized and made consistent from building to building and, in the case of DeepRetro, to allow easy calculation of building level inputs such as overall lighting power density or plug load power based on samples of representative spaces in the building rather than exhaustive counts that take significantly longer to perform.

DeepRetro’s calibration feature for tuning uncertain building parameters based on actual energy use data is an important contribution to the analysis of level I audit data. Without calibration, expensive and time consuming measurements of building subsystems and envelope components would be required, which is outside the scope and budget of a Level I audit. The calibration feature of Deep Retro takes additional computation time, but this time and the associated cost are more rapid and less costly than direct measurement.

Even though DeepRetro requires fewer inputs than other whole building analysis tools, it does account for the effects of interactions among building subsystems and proposed ECMs. Therefore, the energy savings shown for ECM packages on a particular building reflects the total energy savings of an ECM package is necessarily less than the sum of its component elements. Further, DeepRetro will, in future versions, compute the contribution of individual package elements to the energy savings of the entire package. This is a significant advance to the observed state-of-the-art since this type of analysis could previously only be achieved using much more time and information intensive energy analysis tools, such as EnergyPlus and eQuest.

The UQ analysis features allow the building analyst to determine the sensitivity of the building’s simulation results to the input parameters. This, in conjunction with the ability to calibrate uncertain parameters, allows for the range of uncertainty of the results to be quantified. This is not possible for the other tools with which DeepRetro results have been compared. With DeepRetro, the most uncertain results can be highlighted and discounted or allow for further data collection accordingly. Developing this capability will be an important element of BP3.

An accurate calculation of the initial costs of many retrofit options requires detailed information about the building that is not included in the scope of a typical Level I energy audit. The costing methodology assembled reflects assembly levels of detail in alignment with the level of detail and accuracy of the system data collected.

Data Review

Questions about the original data collected emphasized the need for a method of recording the source and confidence of the data collected, such as if building dimensions taken from design drawings or estimated based on square footage. This allows downstream information users of the data to evaluate the reliability of the data based on the defined source and not the assumptions of the reliability of the given auditor. Process-based audit tasks defined protocols are required to improve this data gathering process.

Comparison of Independent Audit Results

Three independent energy audits were performed on building 101 prior to UTRC's audit and analysis. Company A performed a Level II audit while Companies B and C used the same data set from a single Level I audit. The three analyses reported widely divergent results. Only three recommended ECMs were common to all three analyses, and the remainder of the suggested ECMs showed up in only one or two of the audits as shown in Figure 1. In addition, the initial cost and energy savings for the shared ECMs vary widely among the analyses. For instance, the condensing boiler initial cost varies between $73,950 for Company A and $31,215 for Company B. The cost savings are predicted from $ 2909/year for Company A to $1293/year for Company C. The difference in ECMs selected and the costs and savings of each leads to large differences in the total costs and savings from the proposed retrofits Table 1. The case study highlights the need to further study cost estimating methods and to improve their reliability for more accurate ECM definition.

Acknowledgment

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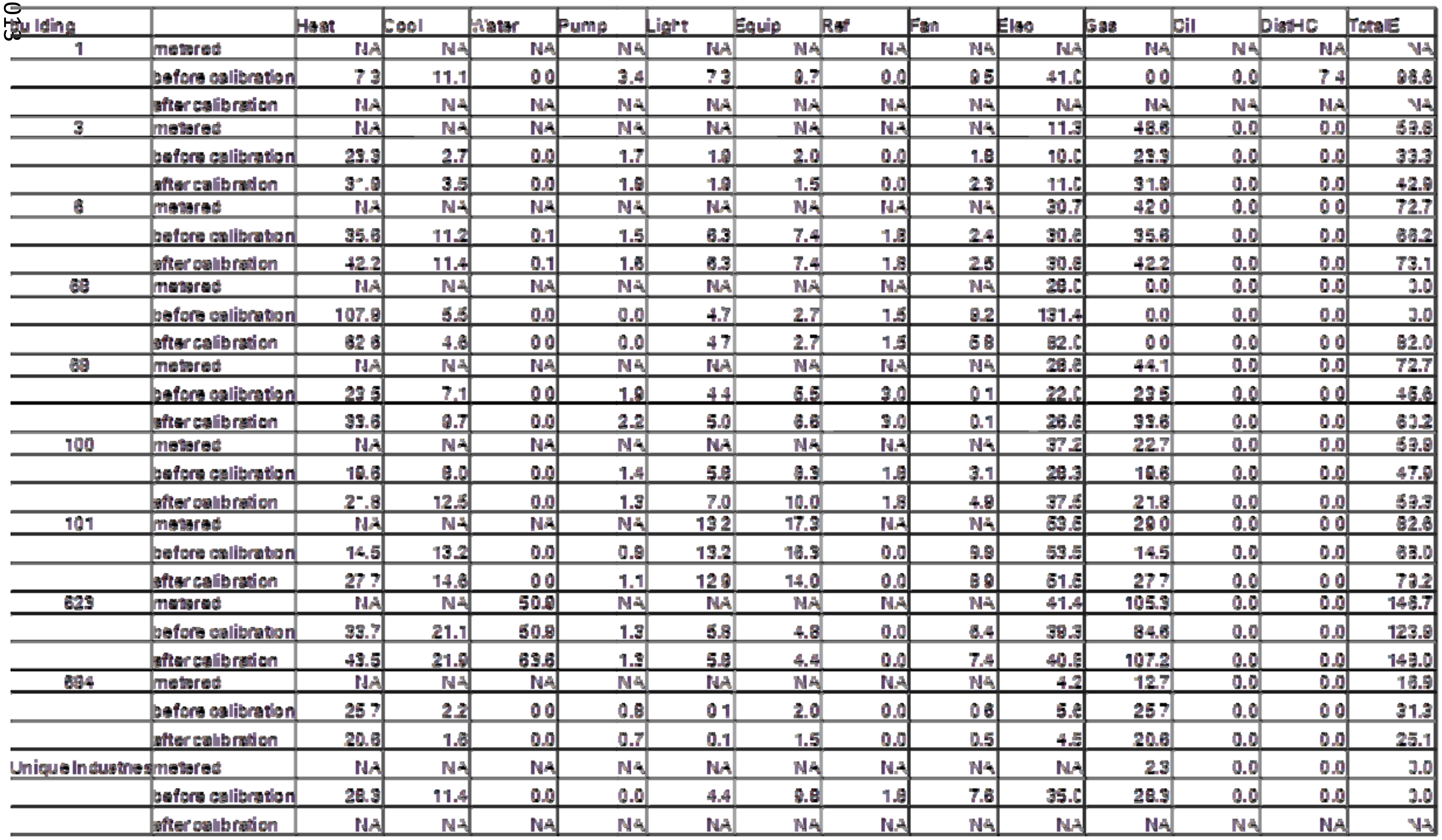
Appendix A: Individual Navy Yard Building Analysis Results

Table A.1 EUI Values for all buildings modeled



Building		Heat	Cool	Water	Pump	Light	Equip	Ref	Fan	Elec	Gas	Oil	DistHC	TotalE
1	metered	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	before calibration	7.3	11.1	0.0	3.4	7.3	9.7	0.0	9.5	41.0	0.0	0.0	7.4	98.8
	after calibration	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	metered	NA	NA	NA	NA	NA	NA	NA	NA	11.3	48.6	0.0	0.0	59.8
	before calibration	23.3	2.7	0.0	1.7	1.9	2.0	0.0	1.8	10.0	23.3	0.0	0.0	33.3
	after calibration	31.9	3.5	0.0	1.9	1.9	1.5	0.0	2.3	11.0	31.9	0.0	0.0	42.9
6	metered	NA	NA	NA	NA	NA	NA	NA	NA	30.7	42.0	0.0	0.0	72.7
	before calibration	35.6	11.2	0.1	1.5	6.3	7.4	1.8	2.4	30.6	35.6	0.0	0.0	66.2
	after calibration	42.2	11.4	0.1	1.6	6.3	7.4	1.8	2.5	30.8	42.2	0.0	0.0	73.1
68	metered	NA	NA	NA	NA	NA	NA	NA	NA	28.0	0.0	0.0	0.0	3.0
	before calibration	107.9	5.5	0.0	0.0	4.7	2.7	1.5	9.2	131.4	0.0	0.0	0.0	3.0
	after calibration	62.6	4.6	0.0	0.0	4.7	2.7	1.5	5.8	82.0	0.0	0.0	0.0	82.0
69	metered	NA	NA	NA	NA	NA	NA	NA	NA	28.6	44.1	0.0	0.0	72.7
	before calibration	23.5	7.1	0.0	1.9	4.4	6.5	3.0	0.1	22.0	23.5	0.0	0.0	45.6
	after calibration	33.6	9.7	0.0	2.2	5.0	6.6	3.0	0.1	26.6	33.6	0.0	0.0	60.2
100	metered	NA	NA	NA	NA	NA	NA	NA	NA	37.2	22.7	0.0	0.0	59.9
	before calibration	19.6	8.0	0.0	1.4	5.8	9.3	1.8	3.1	28.3	19.6	0.0	0.0	47.9
	after calibration	21.8	12.5	0.0	1.3	7.0	10.0	1.8	4.9	37.5	21.8	0.0	0.0	59.3
101	metered	NA	NA	NA	NA	13.2	17.3	NA	NA	63.5	29.0	0.0	0.0	92.6
	before calibration	14.5	13.2	0.0	0.9	13.2	16.3	0.0	9.9	53.5	14.5	0.0	0.0	68.0
	after calibration	27.7	14.6	0.0	1.1	12.9	14.0	0.0	8.9	51.5	27.7	0.0	0.0	79.2
629	metered	NA	NA	50.9	NA	NA	NA	NA	NA	41.4	105.3	0.0	0.0	146.7
	before calibration	33.7	21.1	50.9	1.3	5.8	4.8	0.0	6.4	39.3	84.6	0.0	0.0	123.9
	after calibration	43.5	21.9	63.6	1.3	5.8	4.4	0.0	7.4	40.5	107.2	0.0	0.0	148.0
664	metered	NA	NA	NA	NA	NA	NA	NA	NA	4.2	12.7	0.0	0.0	16.9
	before calibration	25.7	2.2	0.0	0.6	0.1	2.0	0.0	0.6	5.6	25.7	0.0	0.0	31.3
	after calibration	20.6	1.6	0.0	0.7	0.1	1.5	0.0	0.5	4.5	20.6	0.0	0.0	25.1
Unique Industries	metered	NA	NA	NA	NA	NA	NA	NA	NA	NA	2.3	0.0	0.0	3.0
	before calibration	28.3	11.4	0.0	0.0	4.4	9.8	1.8	7.6	35.0	28.3	0.0	0.0	3.0
	after calibration	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Building 3 Analysis and Recommendations

Building 3 is a warehouse formerly used as a cruise ship terminal (Figure A.1).

Figure A.3.1: Front entrance of building 3

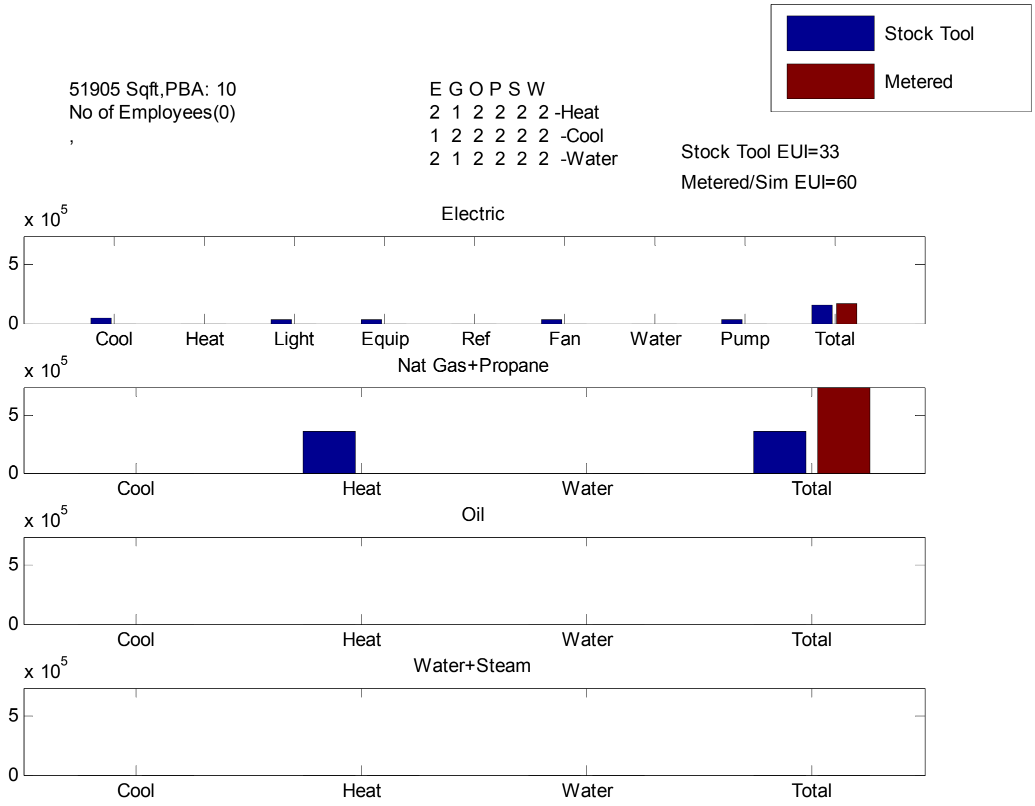


Figure A.3.2: Results of building 3 before calibration

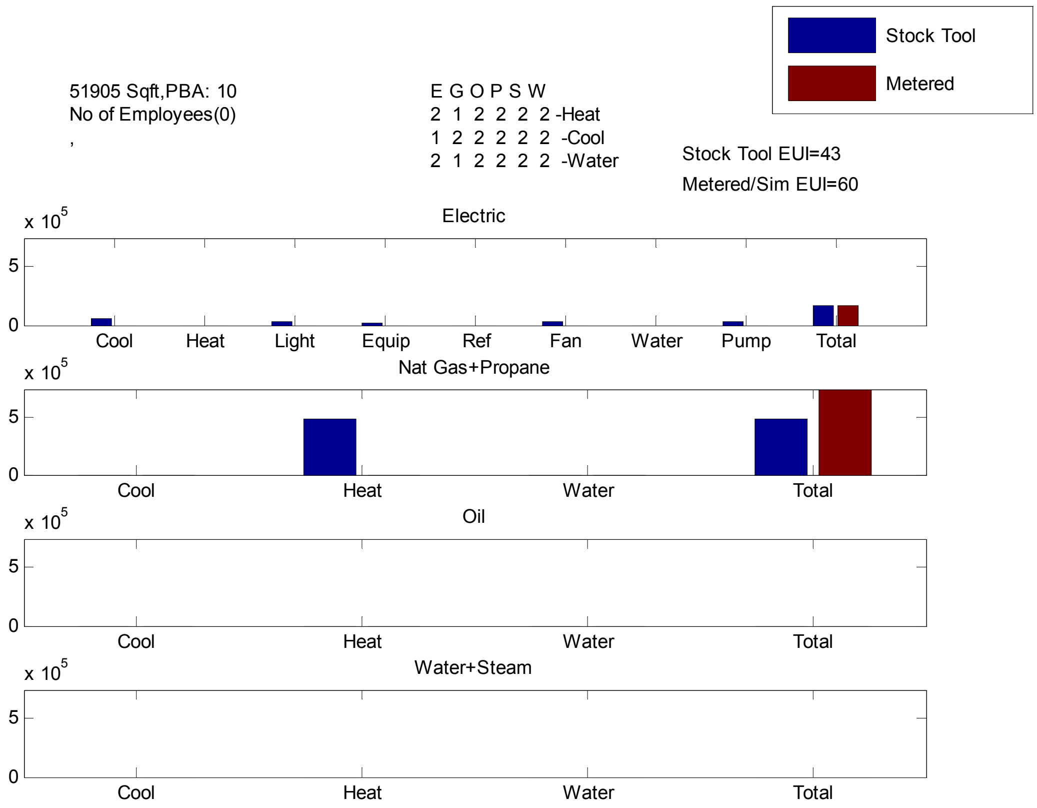
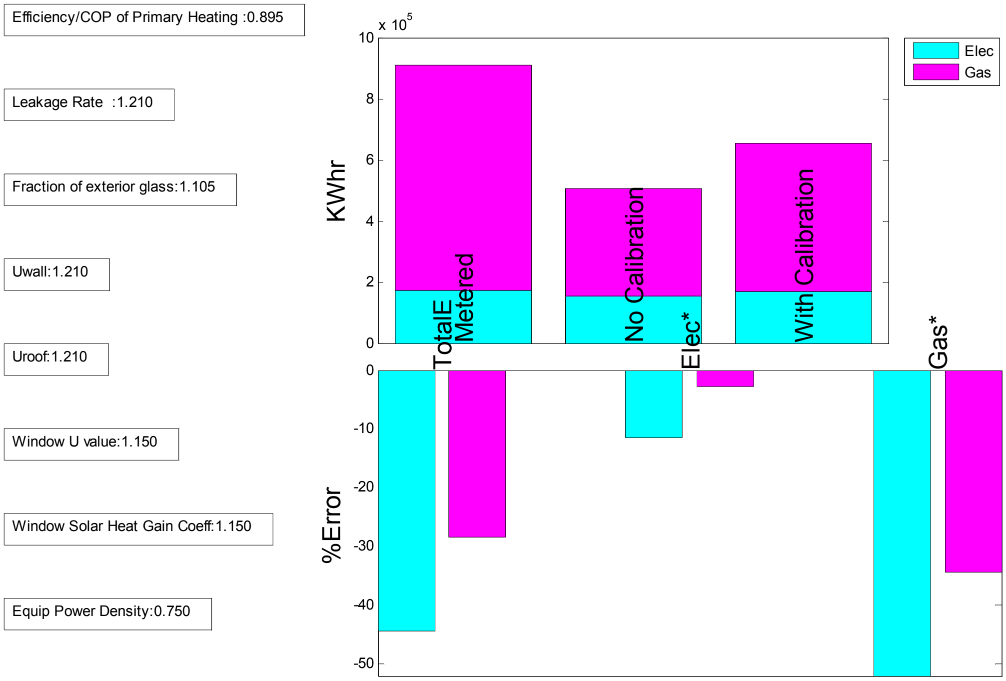


Figure A.3.3: Results of building 3 after calibration


Efficiency/COP of Primary Heating :0.895

Leakage Rate :1.210

Fraction of exterior glass:1.105

Uwall:1.210

Uroof:1.210

Window U value:1.150

Window Solar Heat Gain Coeff:1.150

Equip Power Density:0.750

Figure A.3.4: Calibration graphical output

The ECM packages selected for building 3 are:

- Basic
    - Proper space set point
    - Supply temperature reset
    - Heating plant optimization
    - Daylight based dimming
    - Upgraded lighting
- Moderate
    - Basic ECMs
    - Solar heating
    - Condensing boiler
    - Airside economizer
- Major
    - Moderate ECMs
    - GSHP (no condensing boiler)
    - Added daylight
    - Upgraded insulation
    - Upgraded windows

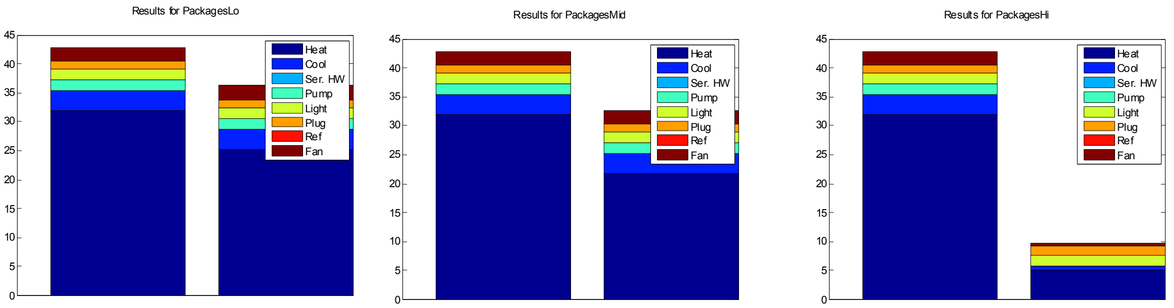


Figure A.3.5: Results from energy analysis of building 3 ECM packages

The simple payback on the low cost package of ECMs is less than one year, while the paybacks on the moderate and high cost packages exceed three years. Therefore it is recommended that the low cost package be implemented.

Building 6 Analysis and Recommendations

Figure A.6.1: Rear of building 6 showing complex planform shape

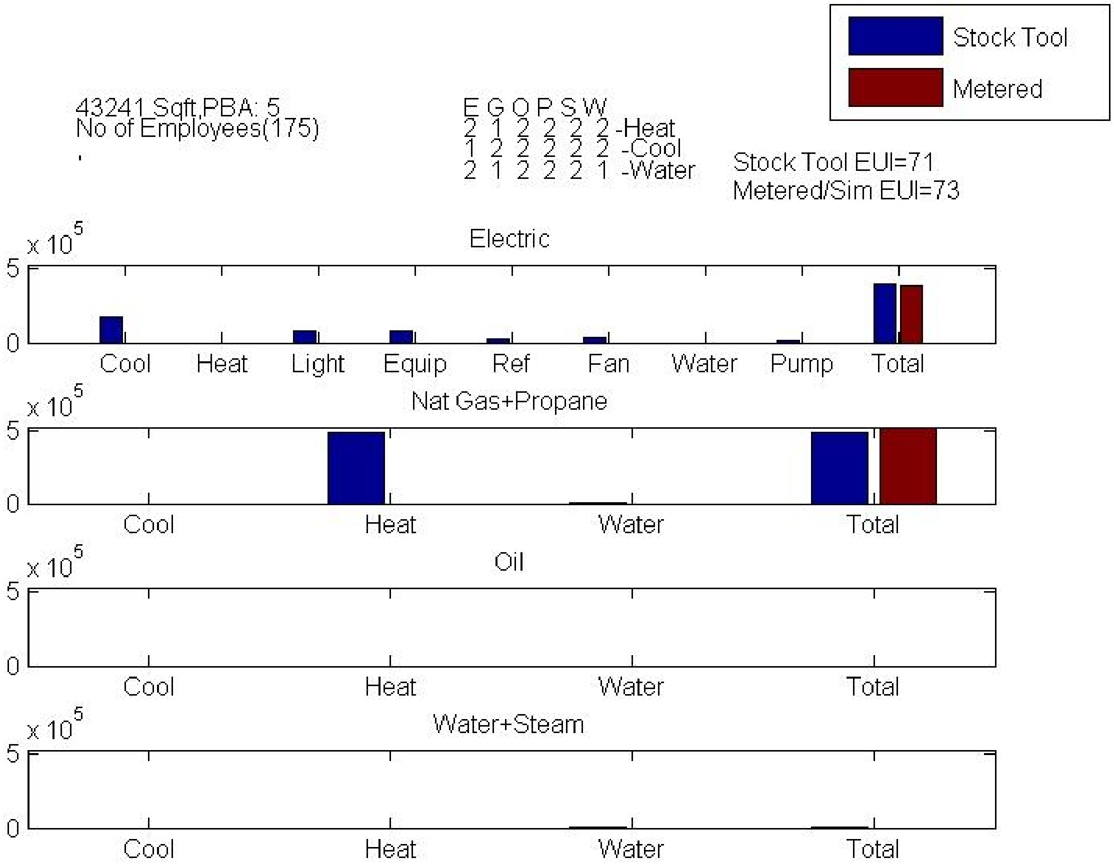


Figure A.6.2: Results of building 6 before calibration

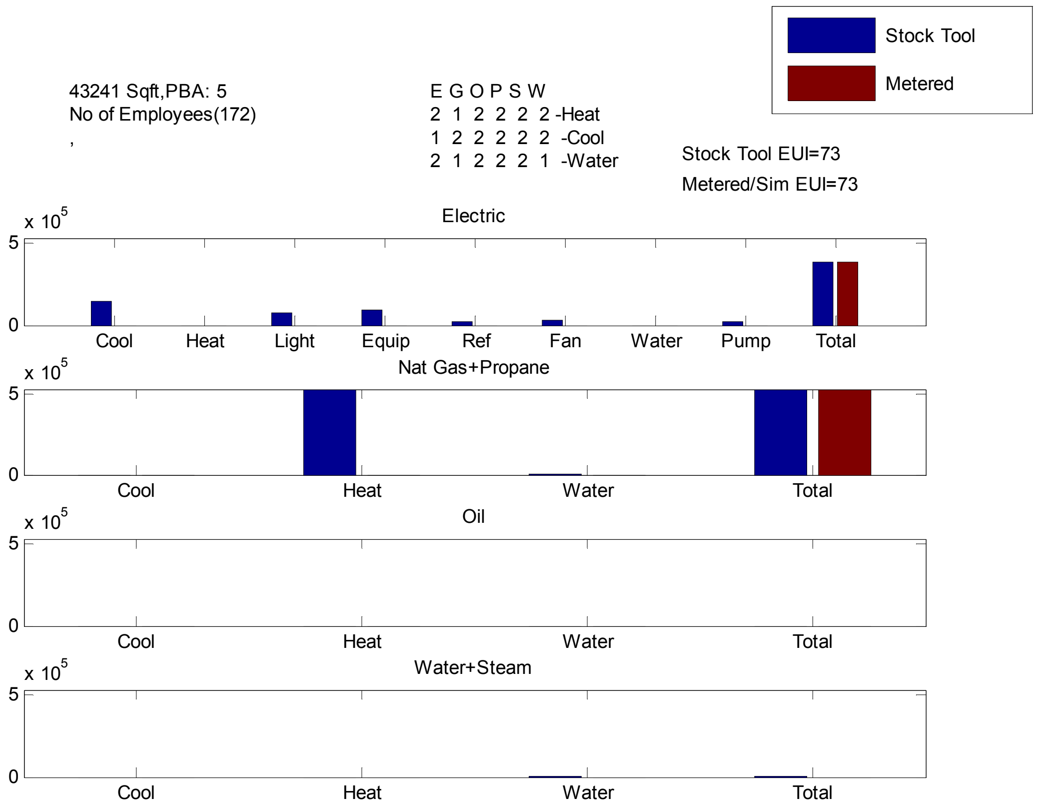
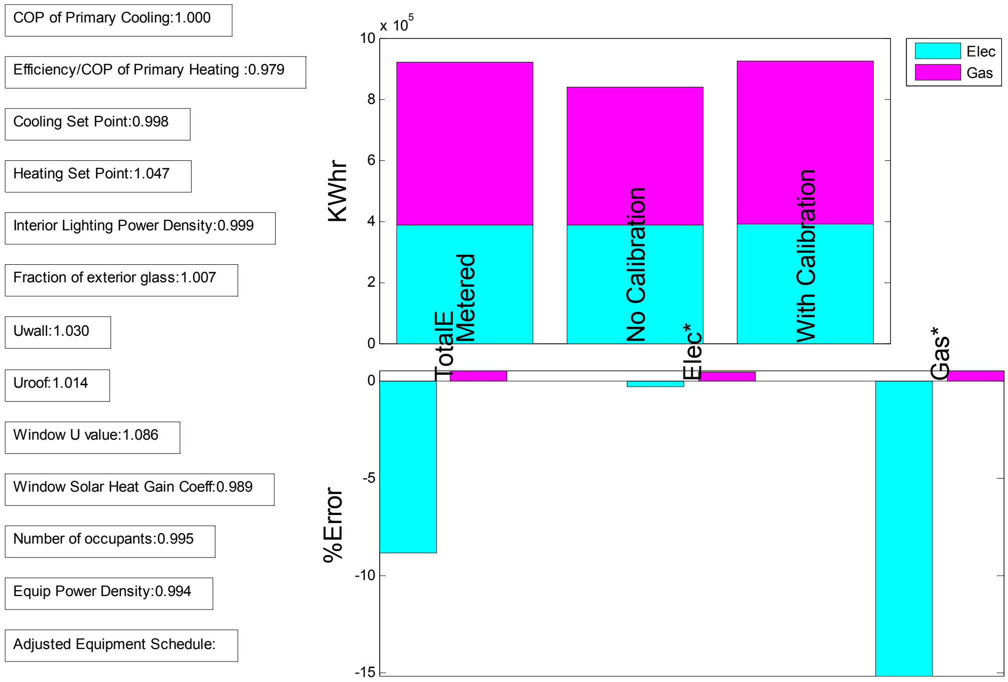


Figure A.6.3: Results of building 6 after calculations



COP of Primary Cooling:1.000

Efficiency/COP of Primary Heating :0.979

Cooling Set Point:0.998

Heating Set Point:1.047

Interior Lighting Power Density:0.999

Fraction of exterior glass:1.007

Uwall:1.030

Uroof:1.014

Window U value:1.086

Window Solar Heat Gain Coeff:0.989

Number of occupants:0.995

Equip Power Density:0.994

Adjusted Equipment Schedule:

Figure A.6.4: Calibration graphical output

The ECM packages selected for building 6 are:

- Basic
    - Proper space set point
    - Supply temperature reset
    - Heating plant optimization
    - Daylight based dimming
    - Upgraded lighting
- Moderate
    - Basic ECMs
    - Solar heating
    - Condensing boiler
    - Airside economizer
- Major
    - Moderate ECMs
    - GSHP (no condensing boiler)
    - Added daylight
    - Upgraded insulation
    - Upgraded windows

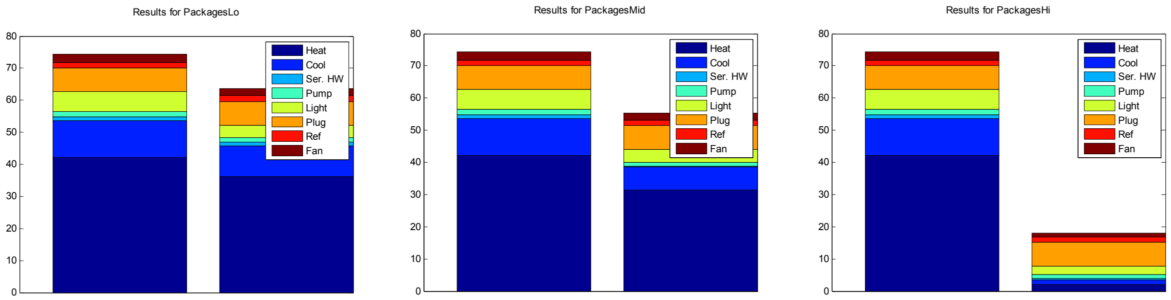


Figure A.6.5: Results from energy analysis of building 6 ECM packages

Building 68 Analysis and Recommendations

Figure A.68.1: Front entrance of building 68

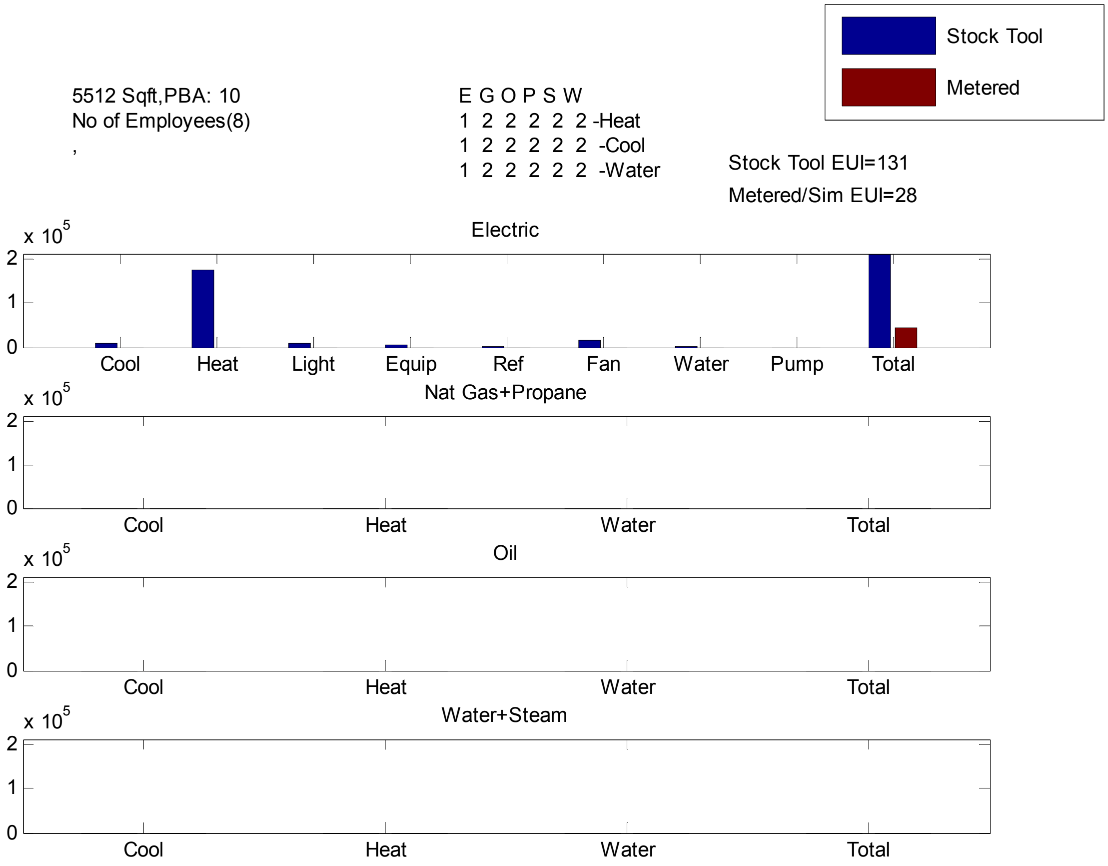


Figure A.68.2: Results of building 68 before calibration

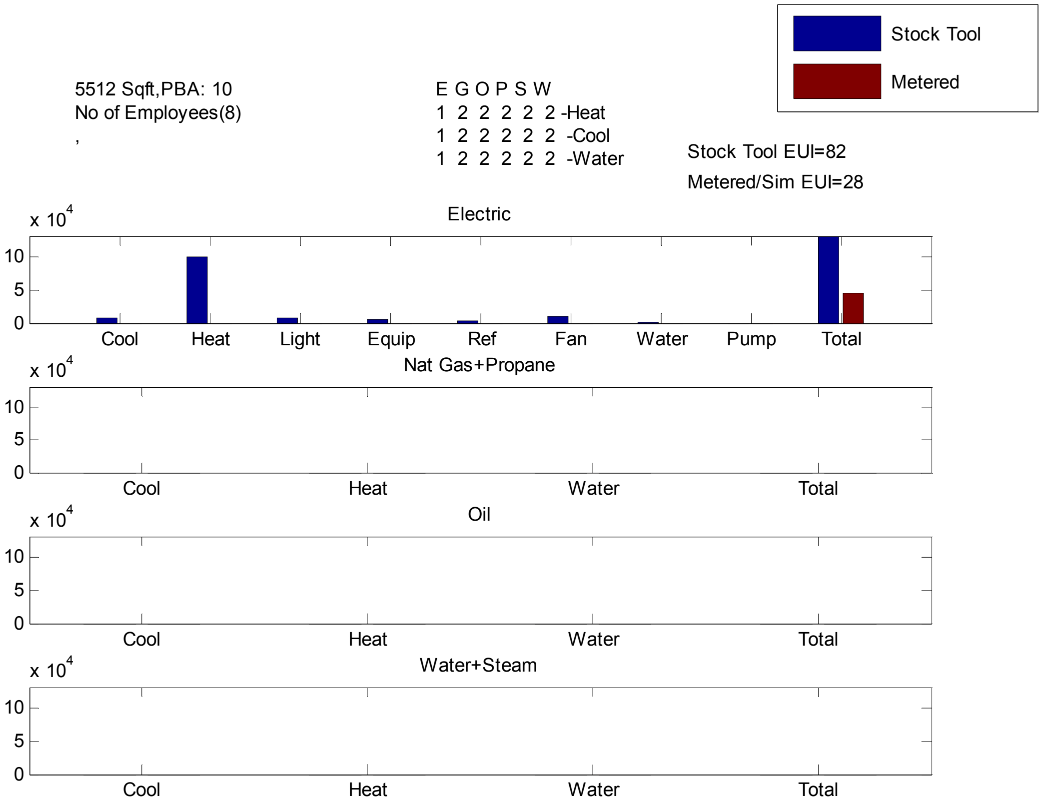


Figure A.68.3: Results of building 68 after calibration

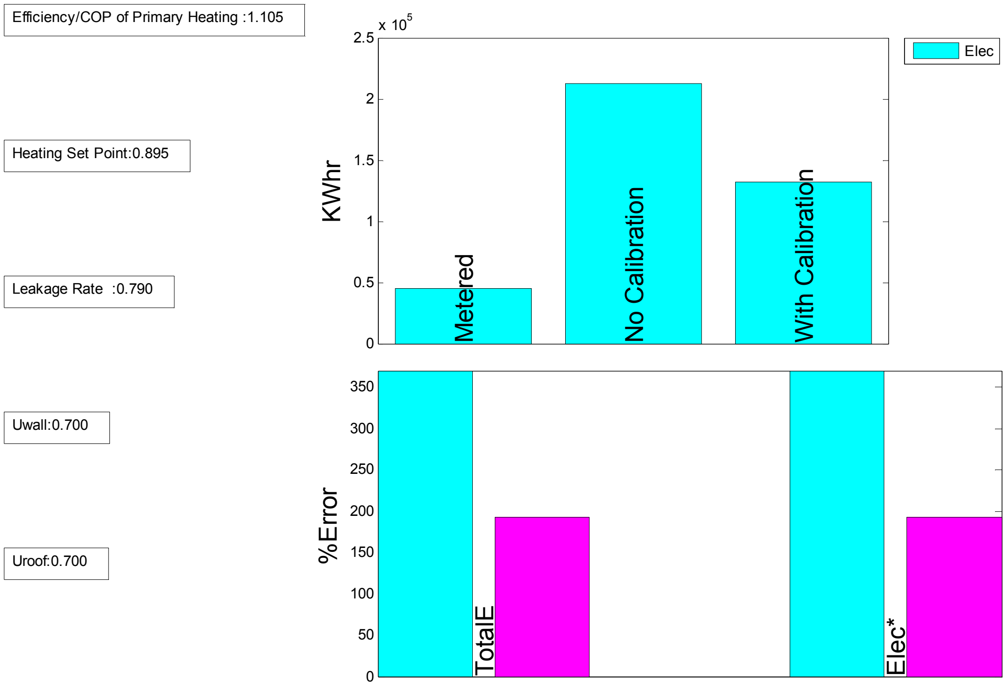


Figure A.68.4: Calibration graphical output

The ECM packages selected for building 68 are:

- Basic
    - Proper space setpoints
    - Weatherization
- Moderate
    - Basic ECMs
    - Solar heating
- Major
    - Moderate ECMs
    - Upgraded insulation
    - Added daylight

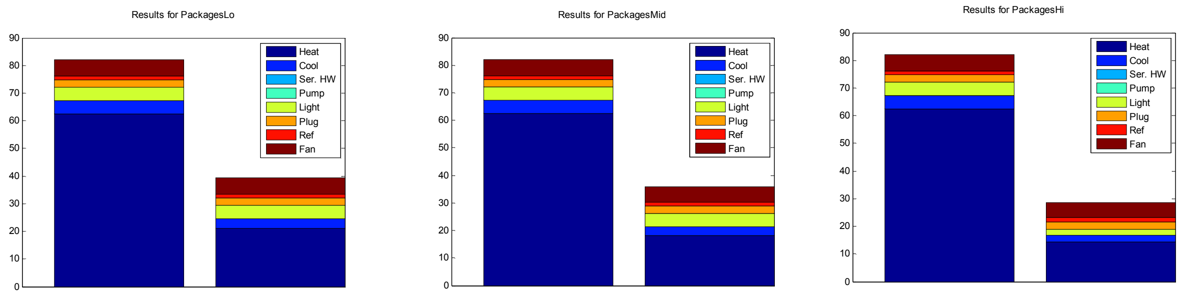


Figure A.68.5: Results from energy analysis of building 68 ECM packages

Building 69 Analysis and Recommendations

Figure A.69.1: Front entrance of building 69

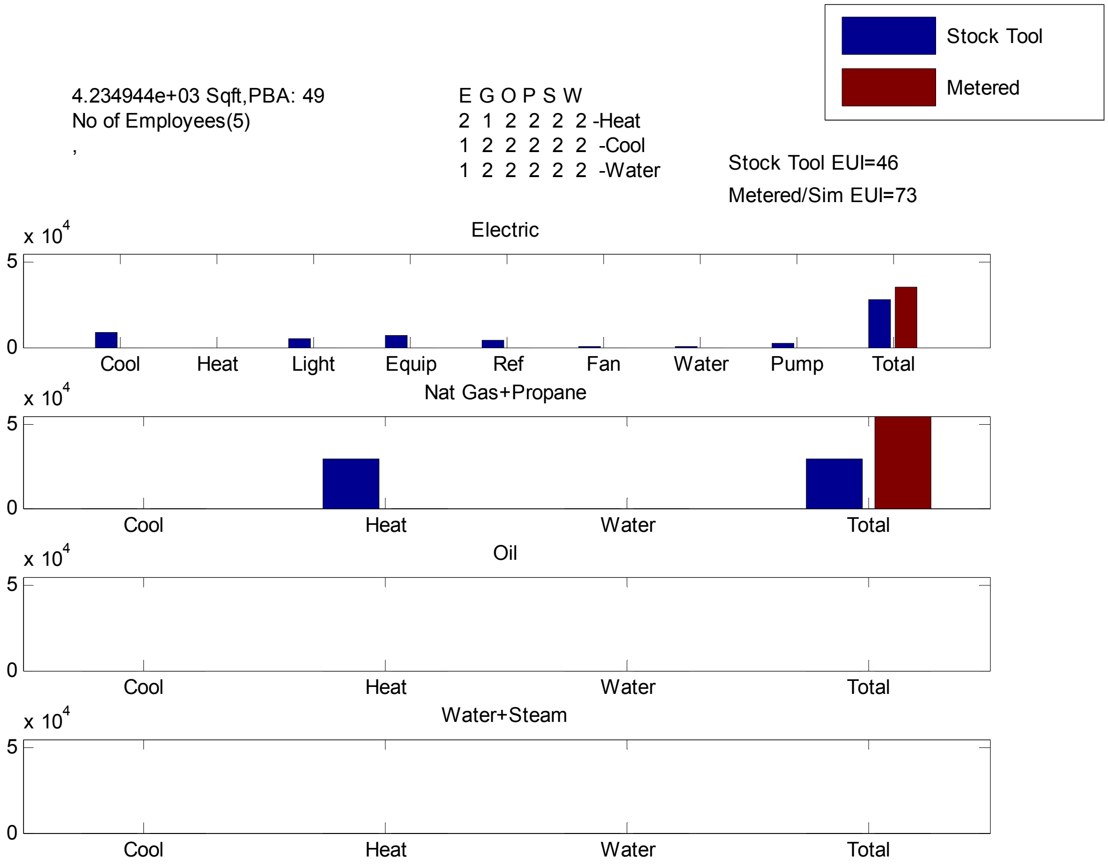


Figure A.69.2: Results of building 69 before calibration

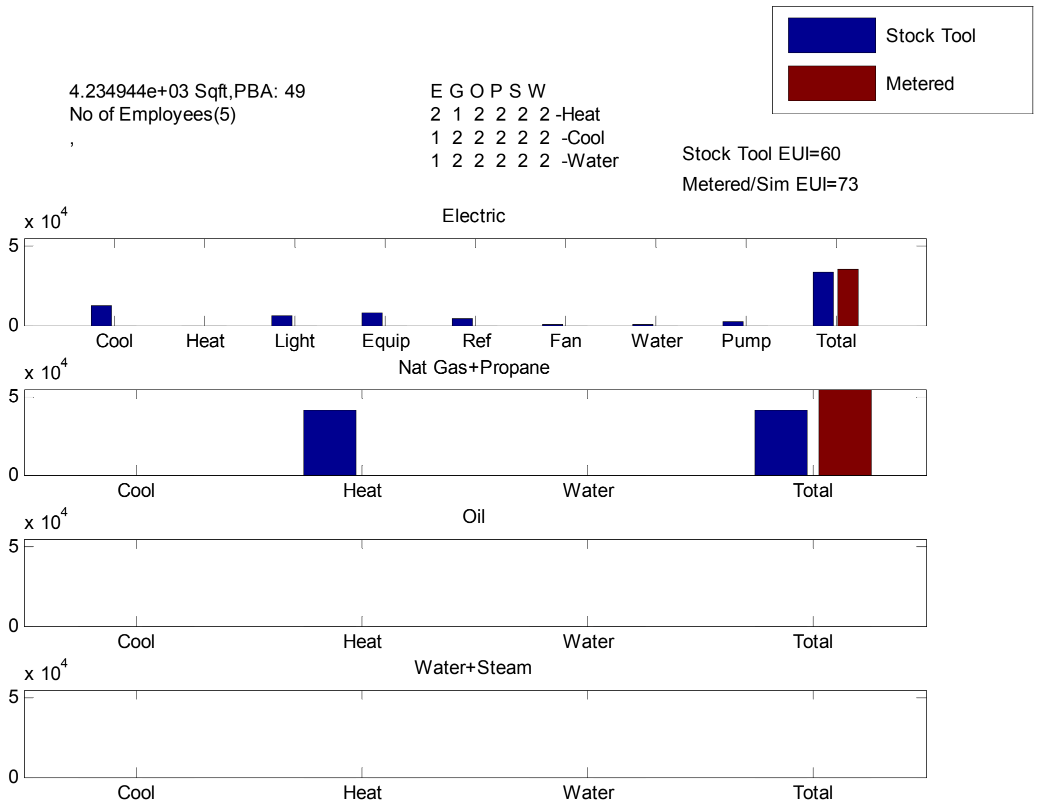


Figure A.69.3: Results of building 69 after calibration

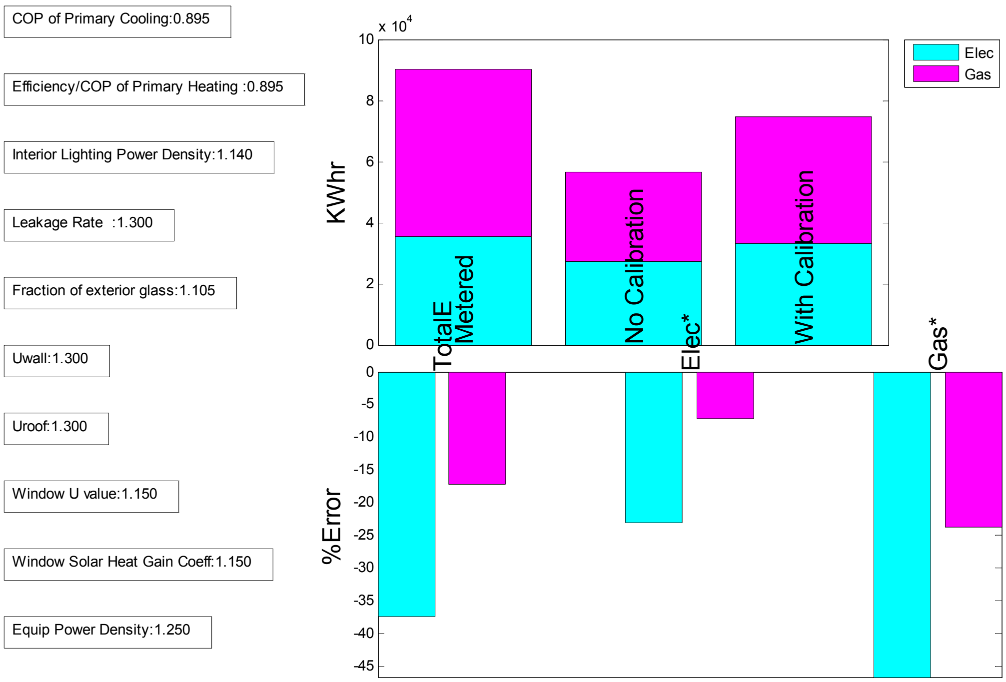


Figure A.69.4: Calibration graphical output

The ECM packages selected for building 69 are:

- Basic
    - Weatherization
    - Proper space setpoints
    - Daylight based dimming
- Moderate
    - Basic ECMs
    - Airside economizer
- Major
    - Moderate ECMs
    - Upgraded insulation
    - Upgraded windows

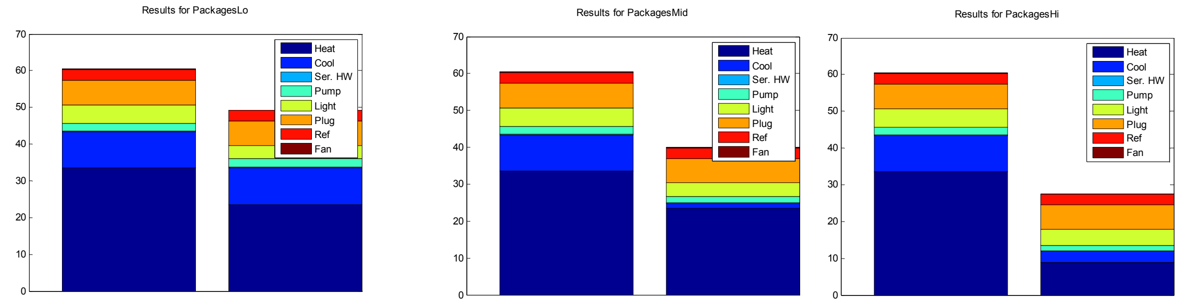


Figure A.69.5: Results from energy analysis of building 69 ECM packages

Building 100 Analysis and Recommendations

Figure A.100.1: Front entrance of building 100

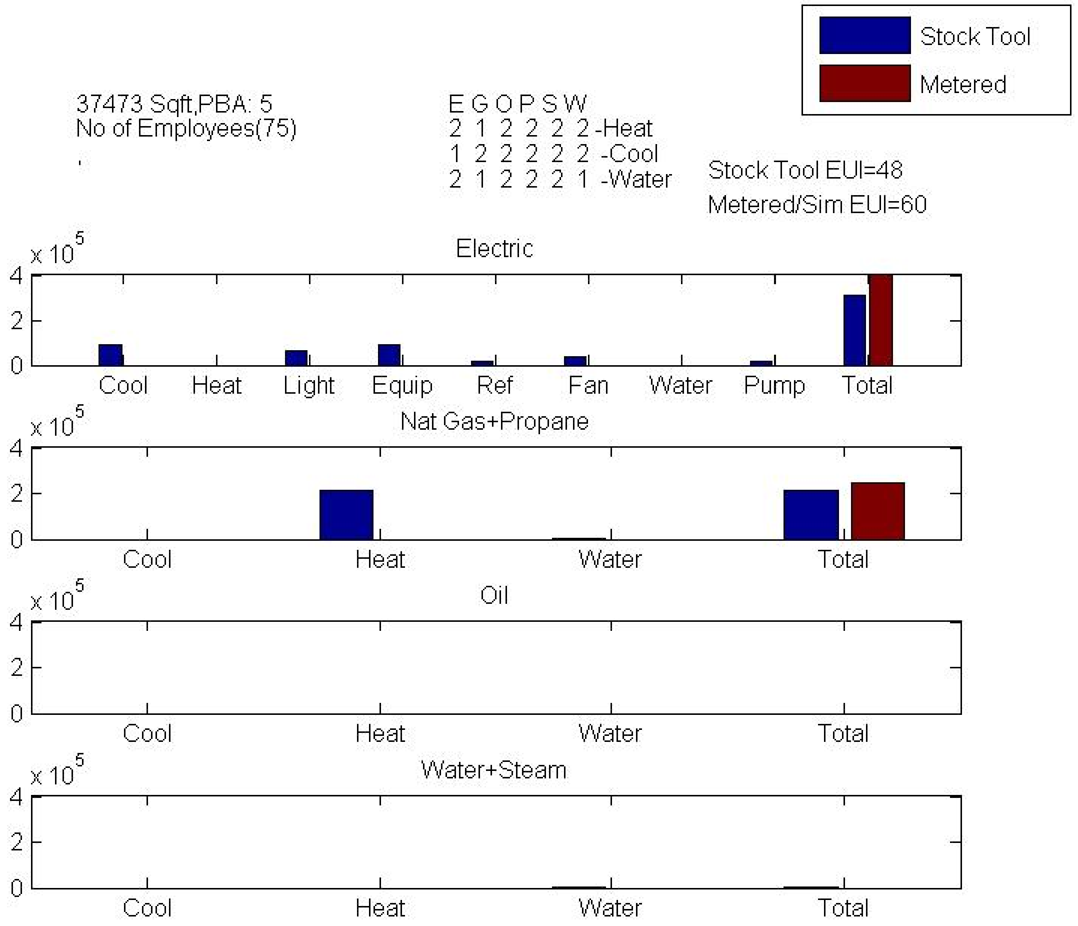


Figure A.100.2: Results of building 100 before calibration

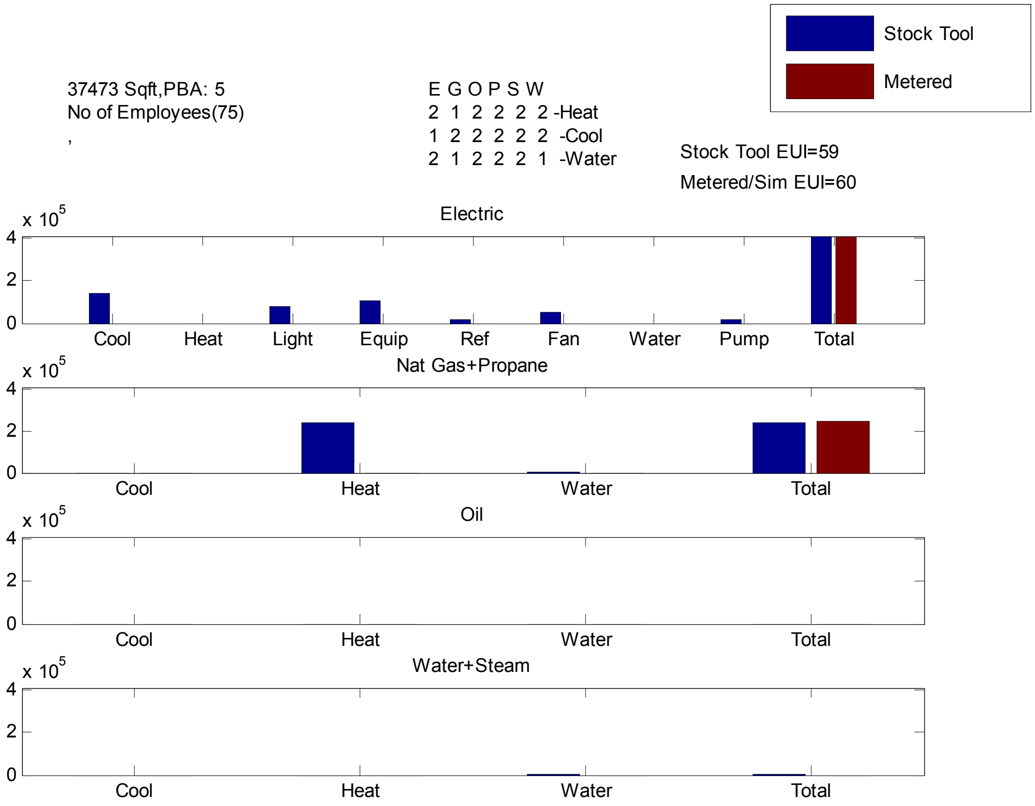


Figure A.100.3: Results of building 100 after calibration

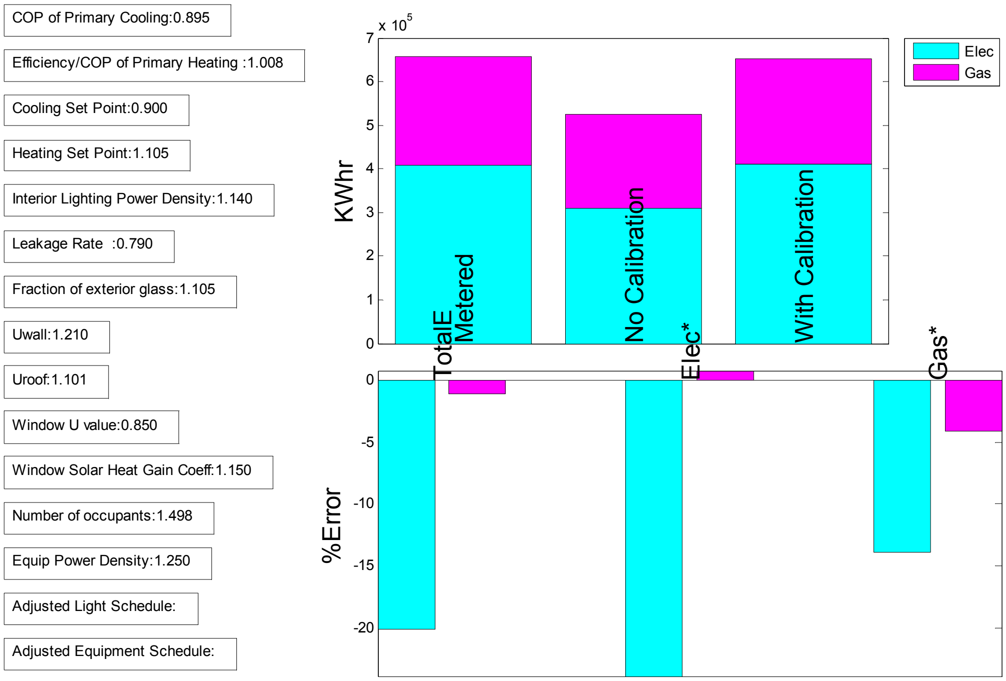


Figure A.100.4: Calibration graphical output

The ECM packages selected for building 100 are:

- Low cost option
    - Proper space set points
    - Daylight based dimming
    - Upgraded lighting
    - Supply temperature reset
    - Heating plant optimization
- Moderate cost option
    - Low cost option
    - Airside economizer
    - Condensing boiler
- High cost option
    - Low cost option + moderate cost option – condensing boiler
    - Upgraded insulation
    - Upgraded windows
    - Ground source heat pump
    - Added daylight

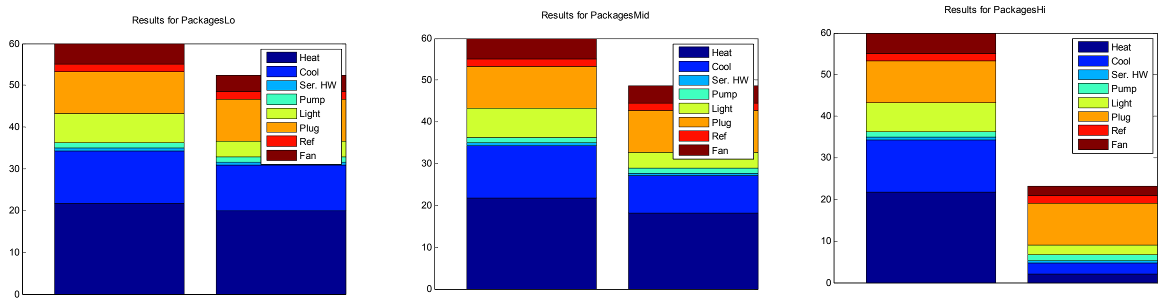


Figure A.100.5: Results from energy analysis of building 100 ECM packages

Building 623 Analysis and Recommendations

Figure A.623.1: Side view of building 623

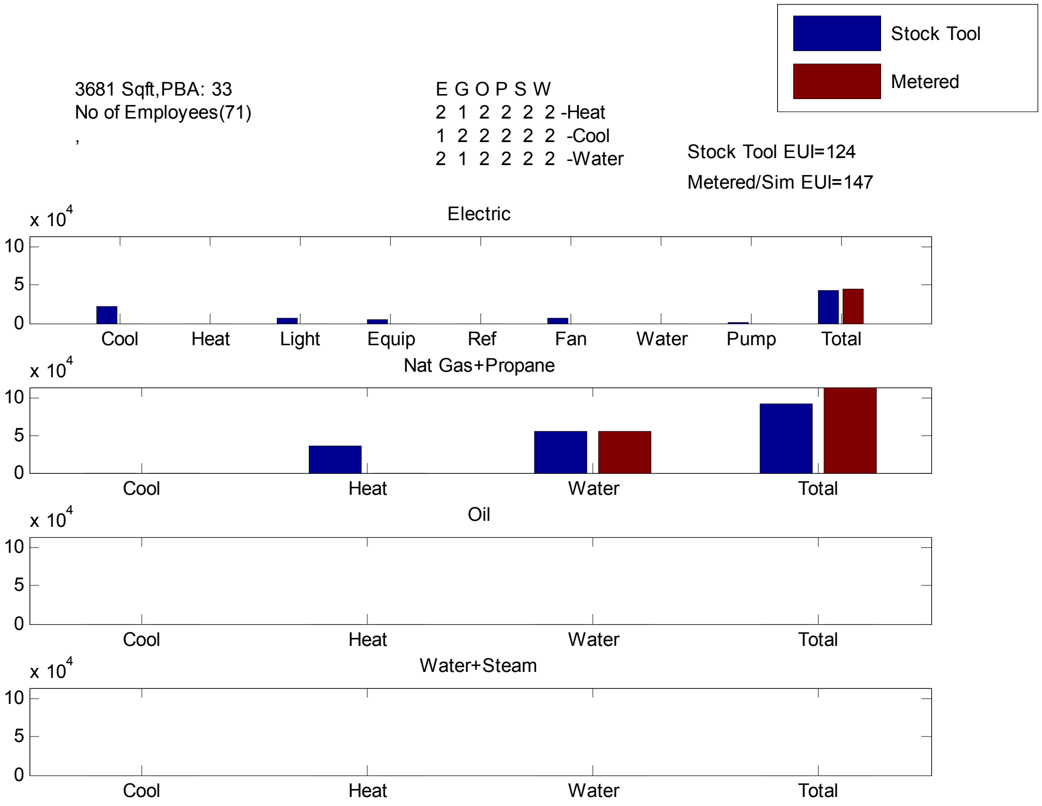


Figure A.623.2: Results of building 623 before calibration

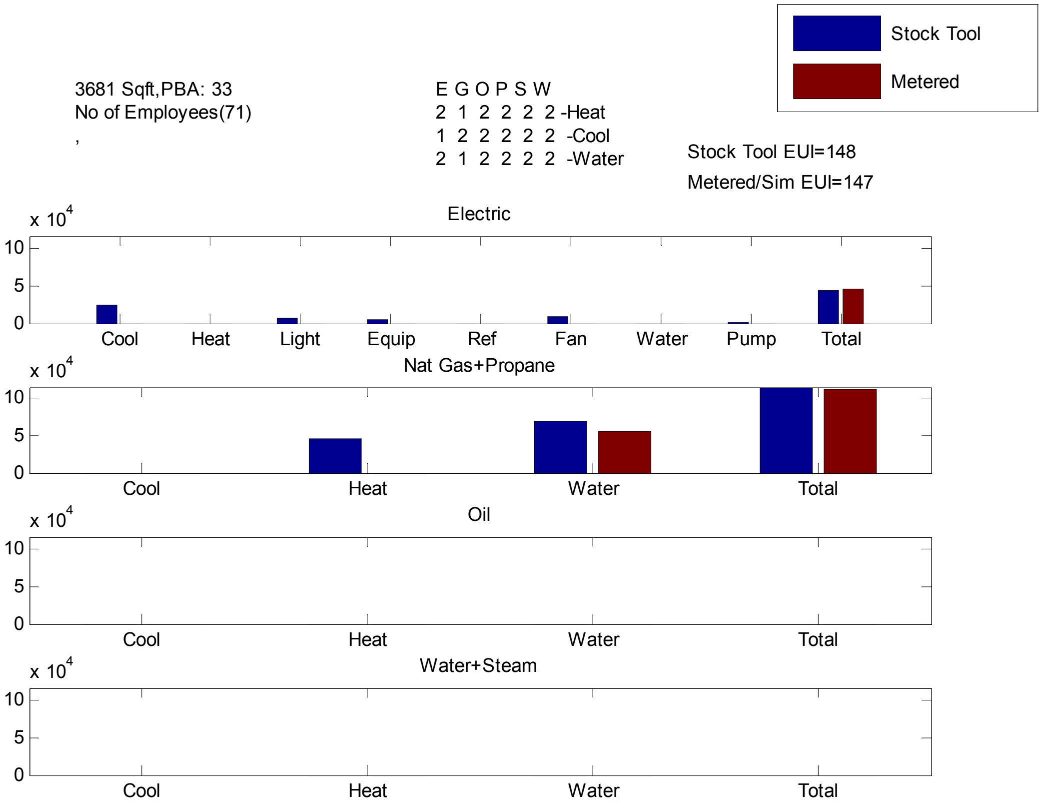
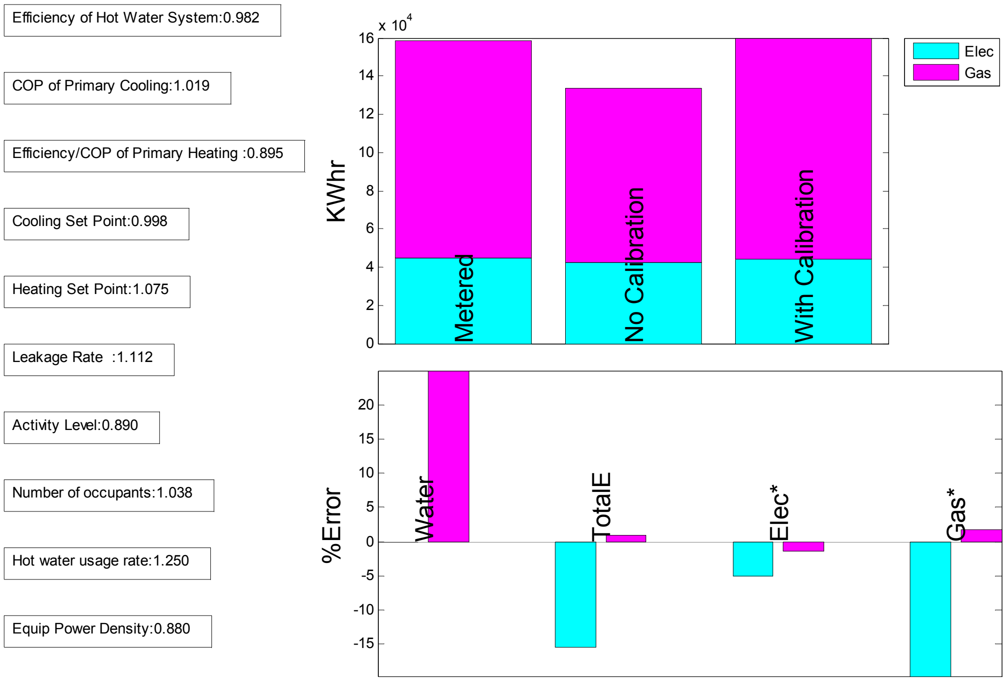


Figure A.623.3: Results of building 623 after calibration


Efficiency of Hot Water System:0.982

COP of Primary Cooling:1.019

Efficiency/COP of Primary Heating :0.895

Cooling Set Point:0.998

Heating Set Point:1.075

Leakage Rate :1.112

Activity Level:0.890

Number of occupants:1.038

Hot water usage rate:1.250

Equip Power Density:0.880

Figure A.623.4: Calibration graphical output

The ECM packages selected for building 623 are:

- Basic
  - Weatherization
  - Proper space set point
  - Tankless water heating
- Moderate
  - Basic ECMs
  - Airside economizer
- Major
  - Moderate ECMS
  - Added daylight
  - Upgraded insulation
  - Desiccant dehumidification

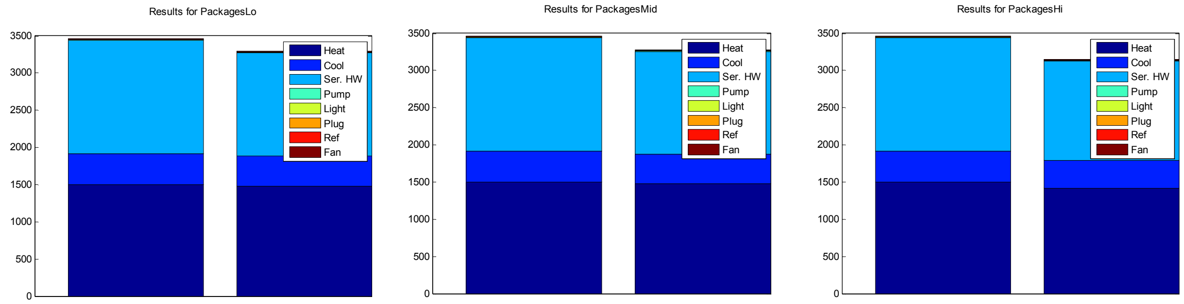


Figure A.623.5: Results from energy analysis of building 623 ECM packages

Building 694 Analysis and Recommendations

Figure A.694.1: Long side of building 694

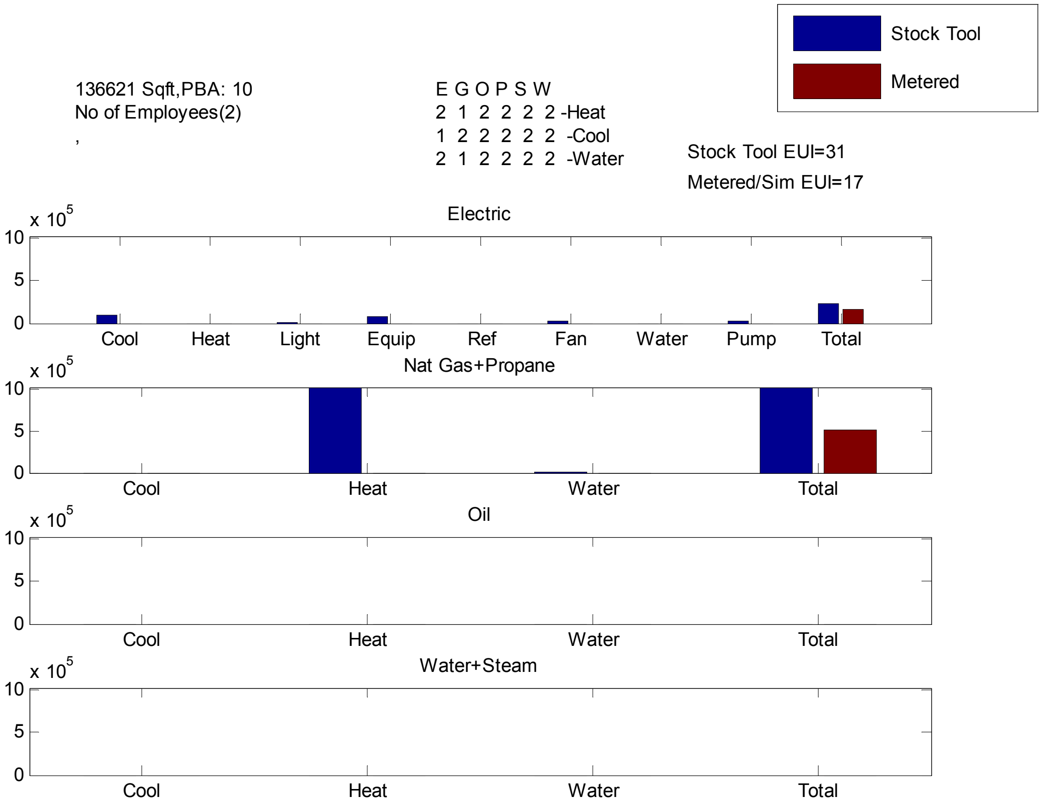


Figure A.694.2: Results of building 694 before calibration

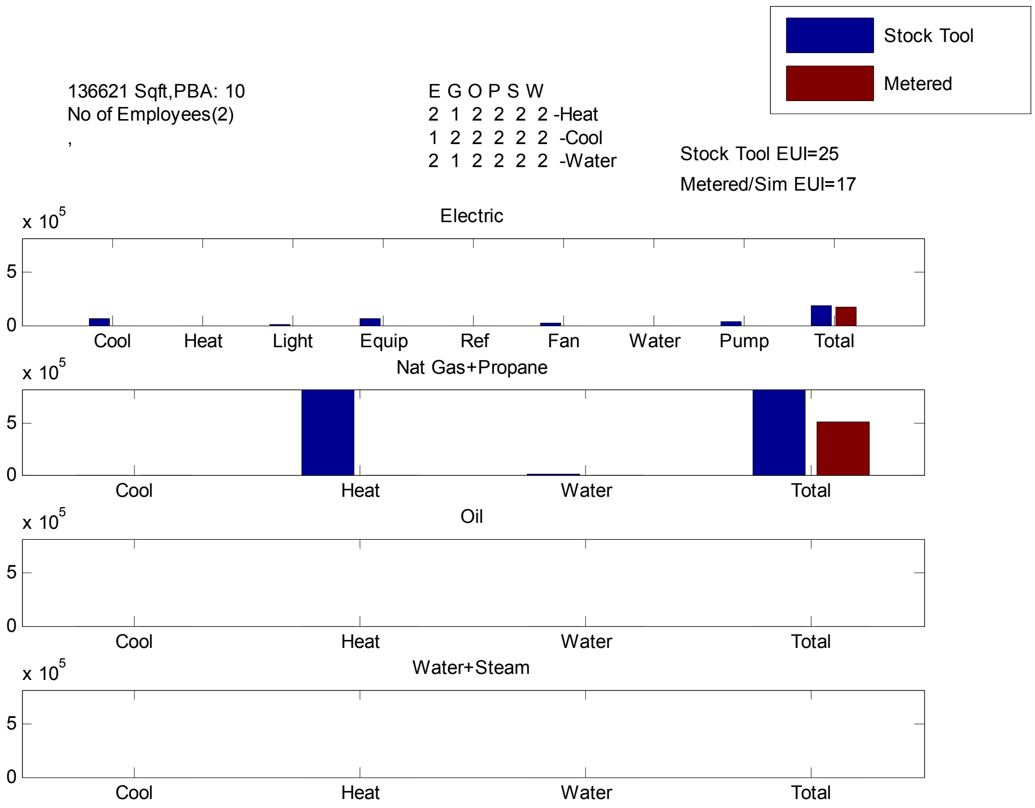


Figure A.694.3: Results of building 694 after calibration

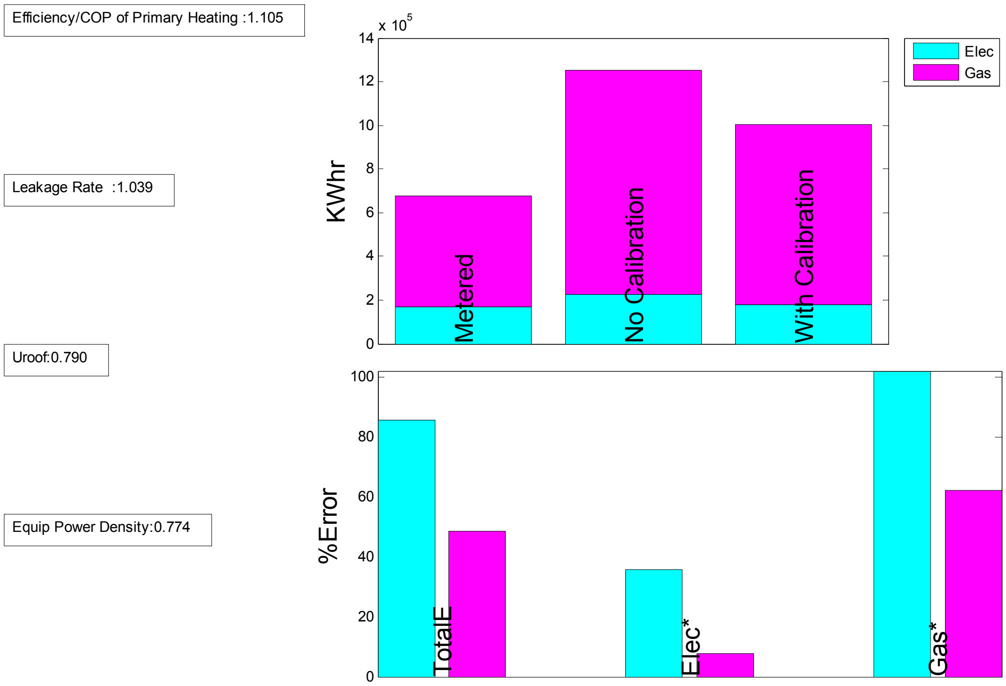


Figure A.694.4: Calibration graphical output

The ECM packages selected for building 694 are:

- Basic
    - Proper space set point
- Moderate
    - Basic ECMs
    - Solar heating
- Major
    - Moderate ECMS
    - Upgrade insulation
    - Green roof
    - Desiccant dehumidification

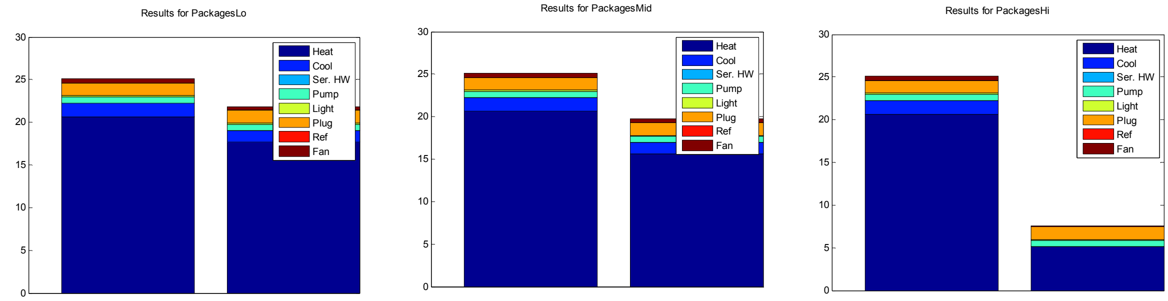


Figure A.694.5: Results from energy analysis of building 694 ECM packages

Economic Results for All Buildings

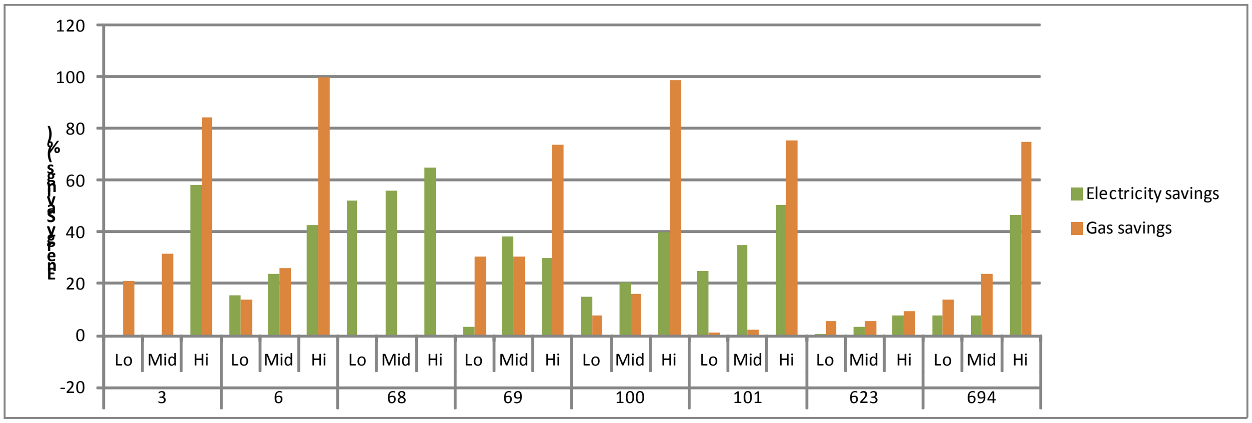


Figure A.1: Percentage energy savings for all buildings and packages

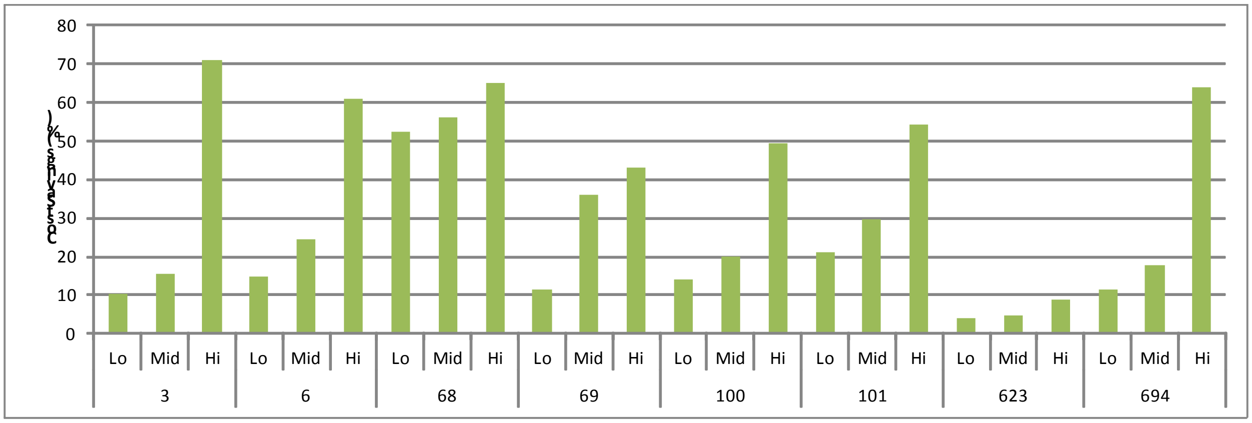


Figure A.2:

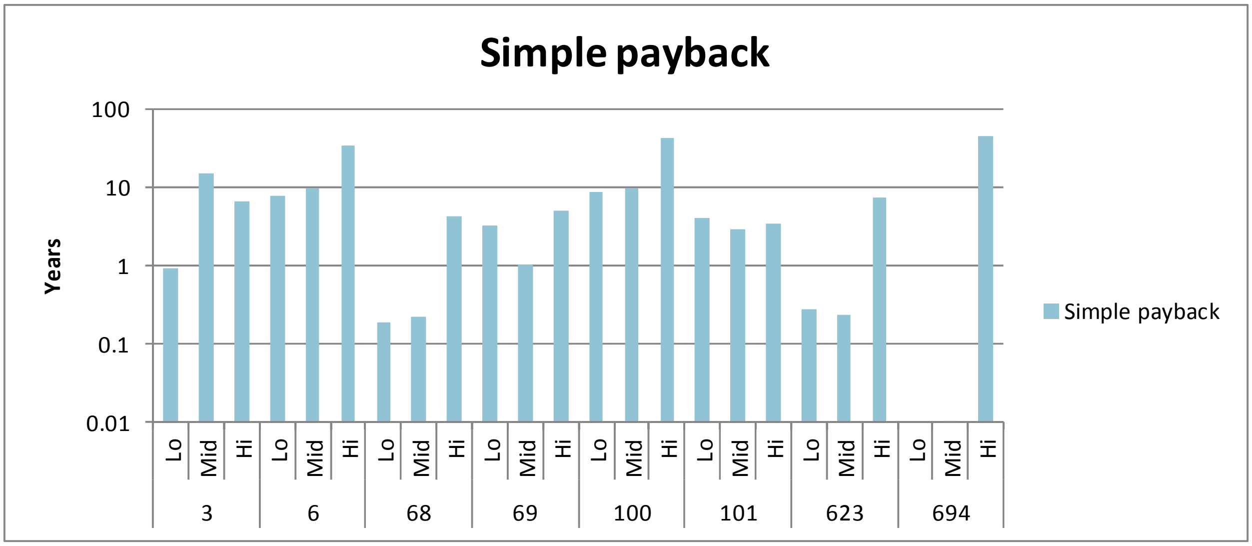


Figure A.3: Simple payback of all ECM packages for all buildings. Note logarithmic vertical scale.

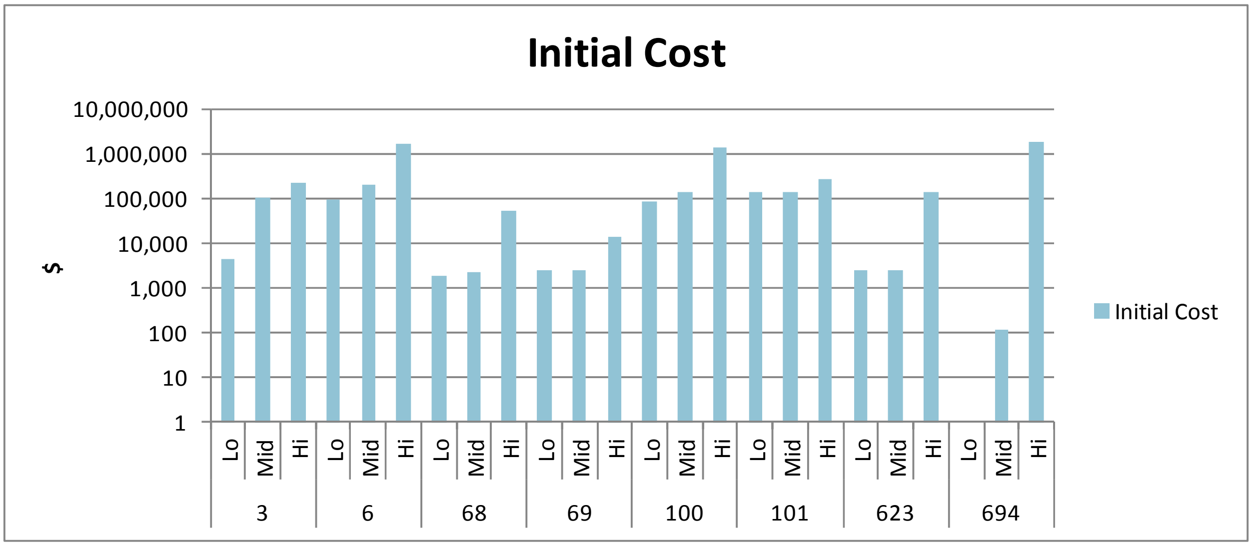


Figure A.4: Capital costs for implementing all ECM packages for all buildings. Note logarithmic vertical scale.

Appendix B: Low Energy Design Principles Energy Conservation Measures Modeled

Lighting and Equipment

- **Light Scheduling**
- **Occupancy Based Lighting Sensors**
- **Daylight Based Dimming**
- **Upgraded Lighting/ Delamping**
- **Plug Load Control**
- **Efficient Equipment (Plug Loads Only)**
- **Light Shelves**
- **Day Lighting (Solar Tubes, Sky lights)**

Envelope

- **Weatherization**
- **Trees**
- **Cool Roof**
- **Upgraded Windows**
- **Increased Insulation**
- **Green Roof**
- **Active External Shading**

HVAC (Terminal side)

- **Air Side Economizer**
- **Fan Assisted Precooling**
- **Modified Setpoint & Setback**
- **Supply Air Temperature Reset**
- **Supply Static Pressure Reset**
- **Water Side Economizer (used in combination with Energy Recovery/ DOAS)**
- **Demand Control Ventilation**
- **Displacement Ventilation + Radiant Cooling/Heating**
- **Under Floor Air Ventilation (UFAD) with Personal Supply Temp Control**
- **Mixed Mode Ventilation**
- **NV for night-time pre-cooling**
- **HVAC Equipment Upgrade**

HVAC (Supply side)

- **CAV to VAV**
- **VAV & Control Retrofit**
- **Chiller Plant Optimization**
- **Heating Plant Optimization**
- **On Demand Service Hot Water**
- **2 Stage Absorption Chillers**
- **Condensing Boiler**
- **Hybrid Ground Source Heat Pump**
- **Energy Recovery**
- **Indirect Evaporative Cooling**
- **Direct Evaporative Cooling**
- **Solar Thermal**
- **Desiccant Dehumidification (used only with Solar Thermal)**
- **DOAS (Used in conjunction with DV +Radiant Systems)**

Lighting Schedule:

A prescribed lighting schedule based on the building usage is used to reduce the lighting load. We use ASHRAE recommendation based on CBECS primary usage category of the building to determine the weekly lighting schedule.

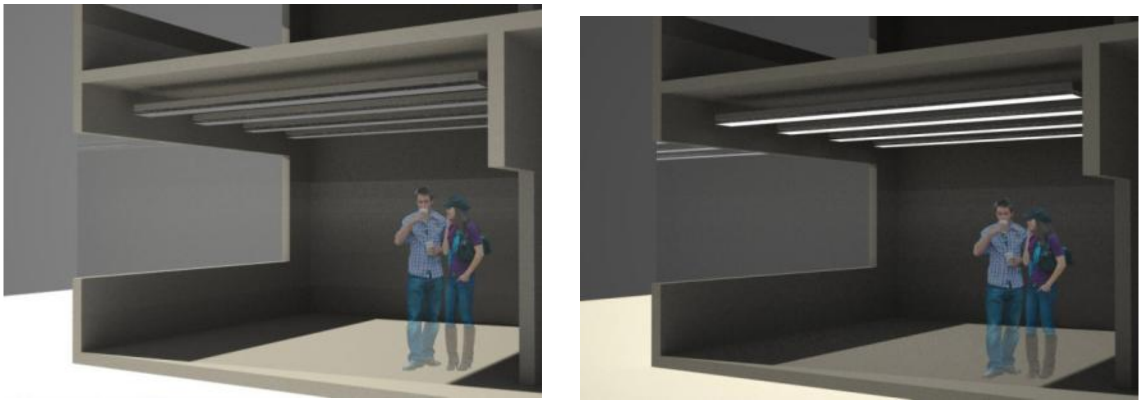
Automatic light controls uses a central controls system to turn off all lights during unoccupied hours. Typically, lights are “swept off” at about 10 pm and allowed to be turned on at about 6 am. During the unoccupied hours a person can override the controls and turn on a specific section of lighting for a pre-determined period of time – typically one or two hours. This is a hard wired or wireless type system with field control panels that communicate with a central EMS or central lighting controls system and program.

Lighting Control Panels that automatically shut off lighting using a time of day schedule have been required by ASHRAE Standard 90.1 since 2001 for new buildings larger than 5000 square feet. A Lighting Control Panel is a scalable controller built on a foundation of low voltage, relay-based control. Lighting Control Panels also interface with many other control devices for easy integration with building automation systems.

Occupancy Sensors:

In this ECM occupancy sensors such as motion detectors are used to turn the artificial lighting on/off based on presence of occupants. Note that this lighting control accounts for actual variability in occupancy, and supersedes the lighting schedule which is solely based on a nominal yearly occupancy pattern. We assume that on an average, occupancy sensors can lead to a 5% reduction in the installed lighting power.

Occupancy Sensors provide automatic ON/OFF switching of lighting loads for enhanced convenience, security and long-term energy savings. The Passive Infrared (PIR) units respond to changes in the infrared background by turning lights ON when people enter space being monitored, and OFF when the space is unoccupied. The Ultrasonic (US) units transmit an ultrasound signal and monitor changes in the signals return time to detect occupancy. Multi-Technology units combine PIR and US sensing technologies for highly accurate monitoring with minimum false triggering. Occupancy sensors should be installed in conference rooms, restrooms, stockrooms, and stairwells in commercial and institutional facilities. Wall switches can be replaced with an occupancy sensor with timer. For the restrooms the times should be set for approximately 10 minutes, should someone be in within a stall for an extended period of time. These systems can be hard wired or wireless.



Daylight Based Dimming

Automatic daylight dimming, or daylighting, uses a light sensor to measure the amount of illumination in a space. Then light output from light fixtures located close to the glazing at the perimeter of the Dining Room can be dimmed or switched off and on to maintain the minimum desired level of illumination. These systems can be hard wired or wireless.

The wireless sensor decreases installation time and costs, and provides retrofit solutions to help buildings become more sustainable and energy efficient. The battery-powered, ceiling mount sensor saves energy by turning off electric lighting when sufficient daylight is available. The sensor detects light in the space and then wirelessly transmits the appropriate commands to a compatible switching device. Those controls then switch off the lights to take advantage of the natural light.

Upgraded Lighting:

Existing buildings typically have older light fixtures that are not as efficient in layout and per fixture efficiency as currently available lighting systems. This involves replacing installed lighting with more efficient T5/CFL/LED lighting fixtures using new lighting fixtures and layout. This gives the best opportunity for savings and for better lighting quality. New technologies have pushed this option to the forefront more often because new lighting design products can significantly reduce the number of fixtures and increase lighting levels and quality. The Lighting Power Density (LPD) for such efficient lighting type is assumed to be 80% of ASHRAE recommended values by CBECS primary usage type.

Plug Load Control:

In this ECM, a prescribed electric equipment load schedule based on the building usage is used to reduce electricity consumption due to equipment's (such as computers/monitors, computer servers, printers, photocopiers, residential refrigerators, vending machine). We use ASHRAE recommended occupancy schedule based on CBECS primary usage type as the equipment load schedule.

Plug load controls saves energy on all types of plug loads such as computer monitors, task lights, radios, copiers, personal printers, space heaters, and more. The equipment will automatically power up when someone approaches it. The built in sensor repeater allows banks of equipment to be controlled with multiple controls using only one sensor. Plug controls can be combined with other lighting controls system. Repeater Cable can be used to power multiple misers using one sensor.

Efficient Equipment:

This ECM involves upgrading the current building electric equipment with Energy Star rated equipment, which meet strict energy efficiency guidelines set by the EPA and US Department of Energy. We assume that on an average, such an upgrade can result in up to 10% reduction in the plug load.

Energy star rated computers, and other appliances and equipment can provide significant energy savings. Any replacement or new equipment should be specified to be Energy Star qualified. The following is a list of categories for such equipment taken from the Energy Star web site.

Appliances

- Clothes Washers
- Dehumidifiers
- Dishwashers
- Freezers
- Refrigerators
- Room Air Cleaners & Purifiers
- Water Coolers

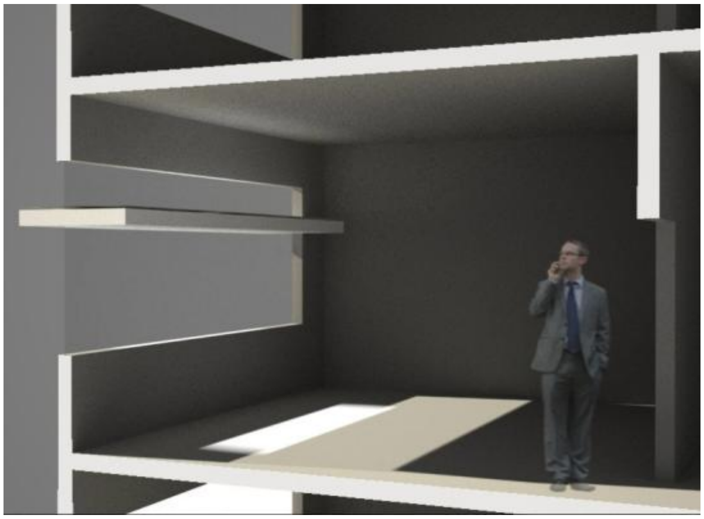
Computers

- Computers
- Displays
- Imaging Equipment
- Uninterruptible Power Supplies

Electronics

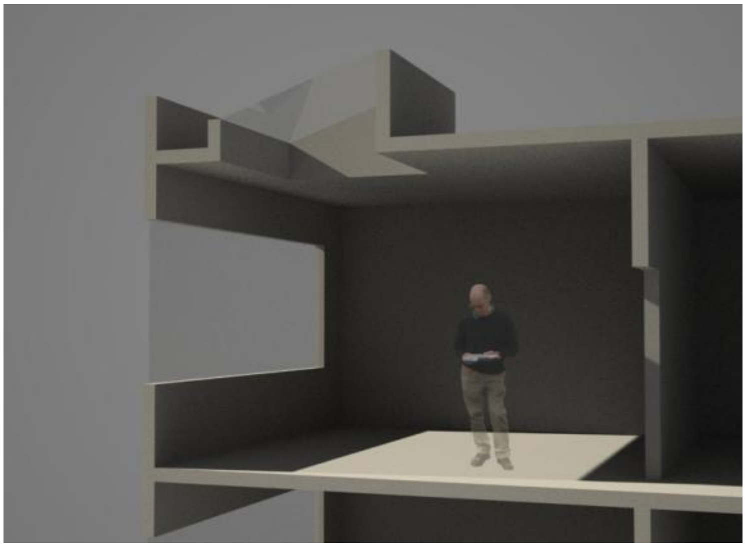
- Audio/Video
- Cordless Phones
- Set-top Boxes & Cable Boxes
- Televisions

Light Shelves:

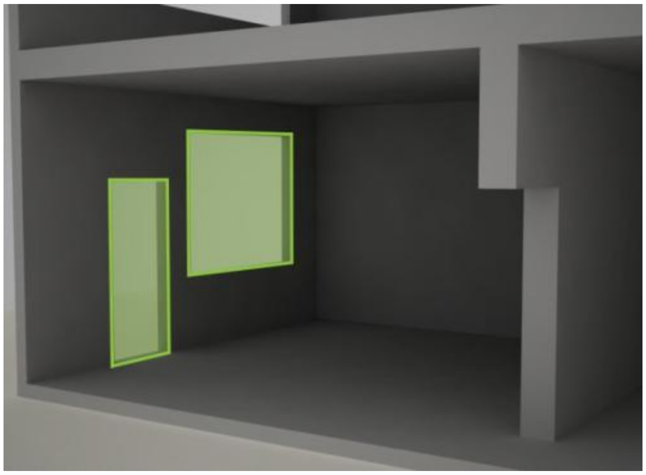


A light shelf is an architectural element that allows daylight to penetrate deep into a building. This horizontal light-reflecting overhang is placed above eye-level and has a high-reflectance upper surface. This surface is then used to reflect daylight onto the ceiling and deeper into a space. Thus, architectural light shelves increase the effective day lit area. The lighting energy savings due to light shelves is computed exactly as described for daylight based dimming, with the modification that the up to 25ft perimeter depth can be day lit (compared to a maximum 15ft when using window based day lighting). Light shelves are generally used in mild climates and are not suitable in tropical or desert climates due to the intense solar heat gain.

Added Daylight (Sky Lights):

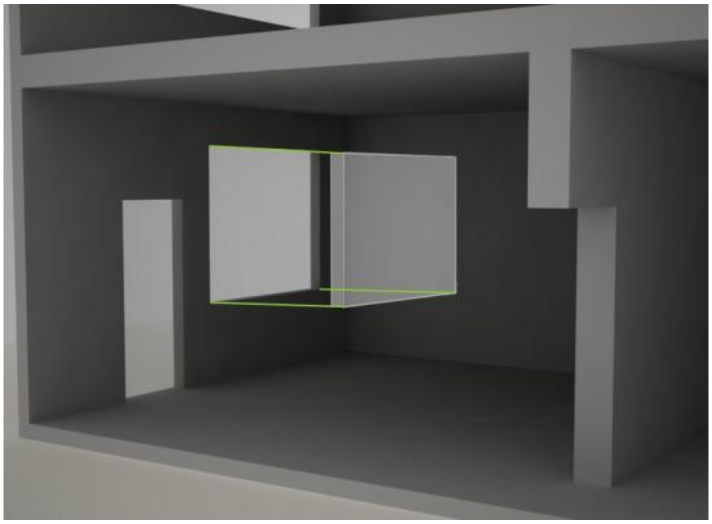


This ECM involves use of skylights to increase day lighting. A skylight is any horizontal window, placed at the roof of the building for day lighting. The optimal area of skylights (usually quantified as "effective aperture") varies according to climate, latitude, and the characteristics of the skylight, but is usually 4-8% of floor area. In general the thermal performance of skylights is affected by stratification, i.e. the tendency of warm air to collect in the skylight wells, which in cool climates increases the rate of heat loss. During warm seasons, skylights with transparent glazing can cause increase in internal heat gains, which are best treated by placing white translucent acrylic over or under the transparent skylight glazing. We assume that due to added daylight the top and the penultimate floor can be day lit up to 75% and 50% respectively.



Weatherization:

It is a practice of protecting a building and its interior from the external elements, particularly from sunlight, precipitation, and wind. Weatherization is distinct from building insulation, although building insulation requires weatherization for proper functioning. Whereas insulation primarily reduces conductive heat flow, weatherization primarily reduces convective heat flow by air tightening the building envelope. Typical weatherization procedure includes sealing of bypasses (e.g. cracks, gaps, and holes), recessed lighting fixtures and air ducts. Weather-stripping at doors and windows can significantly reduce infiltration.



Upgraded Windows:

Upgraded windows use several measures to reduce heat gain and glare, and improve both heating and cooling season performance. Such measures include use of tinted glazing, reflective coatings and films, low-emittance coatings, and assembling various layers of glazing and controlling the properties of the spaces between the layers Thus, by using one or several modifications, windows with different SHGC, thermal conductance and visible transmittance can be constructed. Depending on the weather zone, different window types are recommended for best performance, see Figure to the right (Efficient Windows).

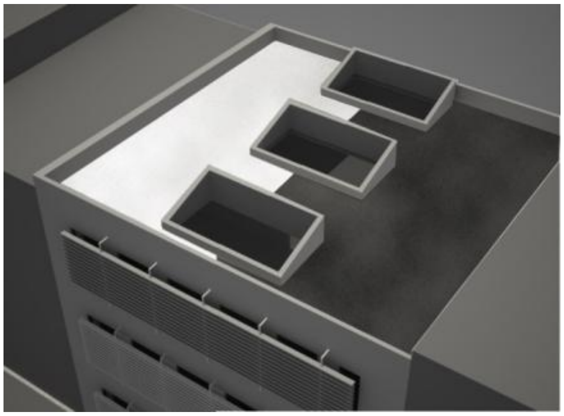
Many times the existing windows are in a state of disrepair. Replacement of the windows with low-e tinted insulated glass with insulated mullions and frames with a thermal break will help reduce the amount of heat and moisture transfer from the exterior of the building. The new windows will translate into reduced load on the HVAC system. If the existing windows are operable consider replacing with fixed glass units. Use a silicone based sealant at the frameopening joint to insure long lasting seal.

In new buildings consider upgrading the glass type to one with a lower SHGC and lower U value. Many times this option will be cost effective in reducing energy use, mechanical loads and mechanical equipment sizes.

Upgraded Insulation:

The conduction load through the building envelope can be reduced by using insulation in wall cavity, to wall exterior or to wall interior, and on the roof exterior. We use ASHRAE recommendation + 2inches of XPS (R10) insulation on the walls, and 4 inches of XPS (R20) insulation on roof. The RTS coefficients were recomputed to account for the upgraded insulation.

Cool Roof:



A roofing system that can deliver high solar reflectance and high thermal emittance. Most cool roofs are white or other light colors and fall into one of two categories: roofs made from inherently cool roofing materials (e.g. thermoplastic white vinyl) or made of materials that have been coated with a solar reflective coating (e.g. ceramic coating). The cooling benefits of a highly reflective roof surface does not outweigh the winter month heating benefits of a less reflective or black roof surface in cooler climates.

A roof can qualify as cool in one of two ways. The first way is by meeting or exceeding both the minimum solar reflectance and thermal emittance values. The alternative way is to meet or exceed the minimum SRI requirement. This allows some roofs that have a low thermal emittance and a high solar reflectance (or vice versa) to still qualify as a cool roof.

Table 1: Typical Minimum Cool Roof Requirements, California Energy Commission

Roof Type	Solar Reflectance [3-year aged]	AND	Thermal Emittance [new or aged]
Low sloped	0.55		0.75
Steep sloped	0.20		0.75

OR

Solar Reflectance Index (SRI) [3-year aged]

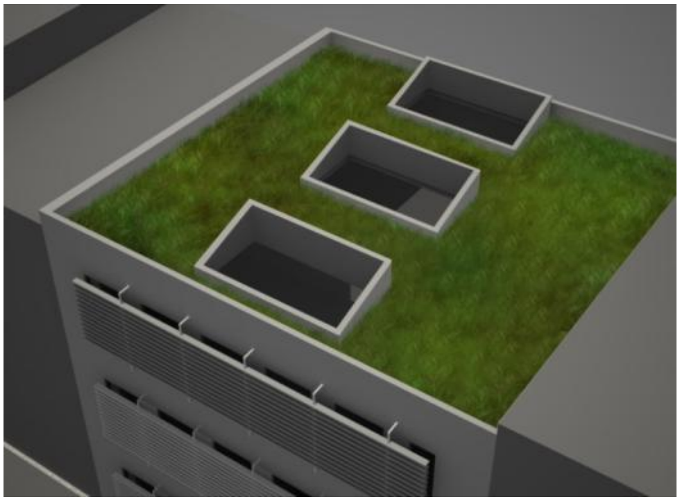
Low sloped	64
Steep sloped	16

Cool roof requirements depend on the roof's slope. Low sloped roofs have a pitch of 9.5° or less (2:12 rise over run), while steep sloped roofs have a pitch greater than this. Requirements are usually less stringent for steep sloped roofs. Some heavier roofs – such as those with concrete pavers, ballast, or vegetation – also have less stringent cool roof standards. The weight of these roofs causes them to heat up more slowly, and during the night some of that stored heat is returned to the outdoor environment.

Others use different cool roof definitions. For example, the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program currently uses minimum aged SRI values of 78 and 29 for low and steep sloped cool roofs, respectively. The U.S. Department of Energy (DOE) has decided to implement cool roofs on all its buildings whenever practicable. The ENERGY STAR program specifies minimum solar reflectance (low slope: 0.65 initial, 0.50 aged; steep slope: 0.25 initial, 0.15 aged) and does not consider thermal emittance.

Green Roof:

A green roof is a roof of a building that is partially or completely covered with vegetation and a growing medium, planted over a waterproofing membrane. It may also include additional layers such as a root barrier and drainage, and irrigation systems. Green roofs reduce heating (by adding mass and thermal resistance value) and cooling (by evaporative cooling) loads. In addition they can increase the roof lifespan.



There are several versions of green roofs:

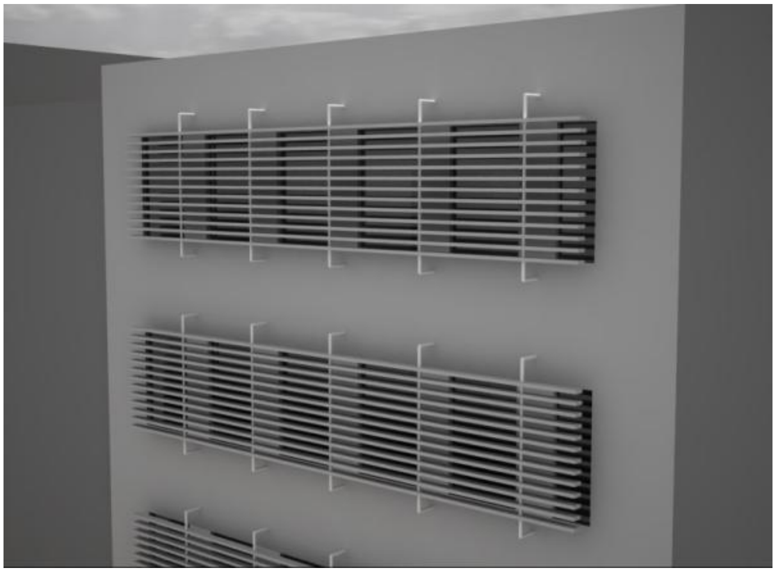
a. With planting that does not require irrigation. Will not look attractive, but will provide the maximum amount of water management benefits. This will detain stormwater runoff and will create a lower effective roof U value.

b. With planting that does require irrigation. Can look attractive, but will not provide the maximum amount of water management benefits. This option will require irrigation, but will detain stormwater runoff and will create a lower effective roof U value. Planting will be more expensive than for option A.

c. With planting that uses captured rainwater and HVAC condensate. Can look attractive, but will not provide the maximum amount of water management benefits. This option will require irrigation during dry seasons, but will detain stormwater runoff and will create a lower effective roof U value.

Each option will require different plant types selected for the growing conditions and local climate that will exist on the roof. There are several systems available for green roofs that use modular "tubs" allowing removal and access to the roof membrane.

Active External Shading (adjustable slats):



External overhangs whether it is a covered front porch, horizontal overhang, arbor, awning, or canopy, can be used to control or avoid direct sun beam shining into the interior to attenuate the adverse glare and contrast, and to lessen the negative contribution of direct sunlight on the cooling load. The value of an overhang is called a "projection factor." The projection factor is the ratio of distance the overhang projects from the window surface to its height above the sill of the window that it shades. However, permanently fixed shading reduces skylight all year, requiring correspondingly larger glazing areas for the same internal daylight levels. Adjustable shades, retractable blinds and awnings, can avoid these problems but have to be strong enough to withstand operation and wind loading.

External solar shading is, in general, more efficient than internal solar shading (for e.g. using curtains, valences, or blinds); though they are more expensive, due to size and the need for robustness.

Roll down type will provide a better overall thermal performance for windows by significantly reducing the SHGC during unoccupied cooling periods and reducing the effective U value during unoccupied heating and cooling periods. Access for maintenance needs to be considered in the envelope design. This type system can be tied into a central EMS and also into local occupancy sensors to maximize the periods of shading.

Louvered type shading is best used as fixed shading, but can be active to respond to the time of day and season. Such systems can provide optimum views while also saving energy.

Trees:

An historic approach to external shading is to use trees and vines. Deciduous trees are particularly suitable as they allow the low level winter sun in when they drop their leaves but will provide shade otherwise. Typically, this will be effective only for one floor buildings. We model the effect of trees in sufficient neighborhood of a building, in same way as the external shading. Specifically, we assume that presence of tress changing the effective SHGC of window glass and absorption coefficient of building envelope only in summer season as follows: In cold climates trees should be located on the north side to provide a winter wind break, and thus, should be evergreen type trees planted close together.

In temperate climates the trees should be located on the east and west sides to provide shade in the peak summer months but also allow sunlight to penetrate in the winter. Thus, trees should be planted 20 feet or so off the east and west sides and be deciduous type.

Air-Side Economizer:

Economizers can save energy in buildings by using cool outside air as a means of cooling the indoor space. When the enthalpy of the outside air is less than the enthalpy of the recirculated air, conditioning the outside air is more energy efficient than conditioning recirculated air. When the outside air is both sufficiently cool and sufficiently dry (depending on the climate), no additional conditioning is needed; this portion of the air-side economizer control scheme is called free cooling. Air-side economizers can reduce HVAC energy costs in cold and temperate climates while also potentially improving indoor air quality, but are most often not appropriate in hot and humid climates without appropriate controls. We used the following control policy to determine the outside air requirement when using the economizer:

An Airside Economizer is an energy saving strategy that takes advantage of favorable weather conditions to reduce energy-consuming mechanical refrigeration by introducing cool outdoor air into a building. The term “free cooling” is used in the HVAC industry to describe savings achieved from an economizer. An economizer consists of a controller, sensors, actuators and dampers that work together to determine how much outdoor air to bring into a building. The controller measures the mixed air temperature and modulates the economizer dampers in sequence to maintain a thermostat indoor temperature set point. The outside air dampers maintain a minimum adjustable position of 20% (adj.) open whenever occupied. Normally an economizer is enabled whenever outdoor air temperature is less than 65°F and greater than 35°F.

Fan assisted pre-cooling:

At some point during the nighttime, the ambient temperature is cooler than the zone temperature by a sufficient amount that it is worthwhile to open the ventilation damper and turn on the fan. When night ventilation precooling is enabled, mechanical cooling is disabled and the ventilation system operates with 100% outside air to precool the zone with a setpoint. If possible, the zone temperature is cooled to a lower (precooling) setpoint and then the fan cycles to maintain this setpoint. The nighttime ventilation leads to lower building surface temperatures, which tends to reduce the heat gains to the air during the daytime and the associated energy and peak power consumption for the mechanical cooling equipment. In addition, night ventilation should be enabled only during the period when the ambient humidity is low enough to avoid increased latent loads during the next day and the ambient temperature should be high enough so as to avoid additional heating requirements after occupancy.

Use the Airside Economizer energy saving strategy to implement a nighttime building flush and pre-cool in the overnight unoccupied hours. An hour or two of fresh outside air in the early morning provides additional free cooling. Nighttime pre-cooling can mean the office is cool when people arrive for work, but will heat up to normal temperatures with the normal activities of the occupants. Savings can be realized by not having to run mechanical refrigeration for the initial period of the work day.

Proper Space Set points:

By properly adjusting the space temperature set points and setbacks, one can significantly reduce the building heating and cooling loads. In this principle a recommended set of temperature setpoints are used, which are determined from the baseline set points (from NREL) as listed in table A.4 below

Implement a 7^{o}F dead band temperature range. Universal set points should be about 68°F for heating and 75°F for cooling for occupied periods. Establish setback points of about 55°F heating and 85°F cooling for unoccupied periods.

Assumes an EMS system is installed or designed for the building. This strategy is required by the 90.1-2007 energy code.

Static Reset:

This principle is based on reducing the fan static pressure until VAV box requiring most pressure is fully open. This can result in up to 5% reduction in the fan power consumption.

As currently controlled, the VAV unit controller measures duct static pressure and modulates the supply fan VFD speed to maintain a duct static pressure set point. The fan speed maintains the duct static pressure and does not drop below 30%. A static pressure reset strategy is based on zone cooling requirements. Initially, the duct static pressure set point is set at 1.5 “w.g. As cooling demand increases, the set point will be incrementally reset up to a maximum of 1.8“w.g. As cooling demand decreases, the set point will be incrementally reset down to a minimum of 1.3 "w.g. The net result is energy savings due to reduced fan power during part load conditions.

Waterside Economizer:

In this measure cooling tower is used to provide chilled water to air handlers when outside air WBT is favorable (i.e. <50°F). This retrofit measure is only applicable when the building already uses a distributed system e.g. fancoils, and is recommended to be used in conjunction with dedicated outside air system (which prohibits the use of air side economizer) for maximum benefit.

Demand Control Ventilation:

Traditionally, the HVAC industry has complied with ASHRAE's standards for indoor air quality with constant ventilation, a control that maintains a desired ventilation set point based on the design occupancy of the space. In contrast, Demand Controlled Ventilation (DCV) uses CO2 sensors to supply outdoor air based on the actual occupancy of the zone - the demand. In the process, it increases indoor air quality and the saves energy normally wasted in ventilating unoccupied spaces. DCV provides a method whereby buildings can regain active and automatic zone level ventilation control, without having to open windows. It allows for the measurement and control of outside air ventilation levels to a target cfm/person ventilation rate in the space based on the number of people in the space.

Demand control ventilation is a method of ensuring a building is ventilated cost effectively while maintaining indoor air quality. Sensors are used to continuously measure and monitor ambient conditions in the conditioned space and provide real time feed. Building ventilation systems often operate at constant or pre-determined ventilation rates regardless of the occupancy level of the building. Ventilation rates are normally based on maximum occupancy levels resulting in consequent energy waste. The energy waste is not only due to the fan operation, but also includes the energy used to condition the air, whether in heating or cooling mode. Significant energy savings are made by effective DCV which ensures that the ventilation rate continuously matches the current CO2-based DCV has the most energy savings potential in buildings where occupancy fluctuates during a 24-hour period, is unpredictable, and peaks at a high level. The technology is recognized in ASHRAE Standard 62, the International Mechanical occupancy rate and varying ambient conditions.

The highest payback can be expected in high-density spaces in which occupancy is variable and unpredictable (e.g., auditoriums, some school buildings, meeting areas, and retail establishments), in locations with high heating and/or cooling demand, and in areas with high utility rates.

Displacement Ventilation and Radiant Systems:

Displacement Ventilation (DV) systems introduce air into the space at low velocities which causes minimal induction and mixing. Dis-placement outlets may be located almost anywhere within the room, but have been traditionally located at or near floor level. The system utilizes buoyancy forces, generated by heat sources such as people, lighting, computers, electrical equipment, etc. in a room to remove contaminants and heat from the occupied zone. By so doing, the air quality in the occupied zone is generally superior to that achieved with mixing ventilation. Since the conditioned air is supplied directly into the occupied space, supply air temperatures must be higher than mixing systems (usually above 63 degrees F) to avoid creating uncomfortable drafts. By introducing air at elevated supply air temperatures and low outlet velocity a high level of thermal comfort can be achieved with displacement ventilation. Due to the heavy heat loads found in today's offices, the displacement ventilation system is often teamed with radiant chilled ceilings to enhance the cooling effect.

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Displacement ventilation presents an opportunity to improve both the thermal comfort and indoor air quality (IAQ) of the occupied space. Displacement ventilation takes advantage of the difference in air temperature and density between an upper contaminated zone and a lower clean zone. Cool air is supplied at low velocity into the lower zone. Convection from heat sources creates vertical air motion into the upper zone where high level return outlets extract the air. In most cases, these convection heat sources are also the contamination sources, i.e. people or equipment, thereby carrying the contaminants up to the upper zone, away from the occupants.

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Under Floor Air Distribution:

UFAD uses the open space between a raised floor and a structural concrete slab to deliver conditioned air directly into the occupied zone of the building, most commonly through floor-level supply outlets. Well-designed UFAD systems offer several advantages over conventional overhead (OH) air distribution systems: 1) Increased flexibility and reduced life-cycle costs through the use of a raised access floor system, and 2) Improved ventilation effectiveness and indoor air quality (IAQ) by delivering fresh supply air through floor diffusers close to occupants. Under cooling operation, properly controlled UFAD systems produce temperature stratification in the conditioned space. Energy savings for UFAD compared to CAD systems were originally projected in 2002 and 2003 by both Air Conditioning and Refrigeration Technology Institute 21st century and York Corporation to range from 20% to 35%.

However, these reports of such savings did not square with actual UFAD installations, which lead to the following conclusions:

Air leakage of 40% to 210% of the design plenum supply air flow rates was measured during testing. Such extreme leakage makes thermal control difficult at best, and the energy waste monumental.

Since the supply air must be at elevated temperatures when introduced at ankle level, almost twice as much air is required than with ceiling diffusers. What an energy penalty.

Conversion from CAV to Variable Air (w/VFD):

Constant air volume systems are often oversized and incur a significant energy penalty due to their incapability of modulating airflow. Zone loads are often much lower than the design load due to partial occupancy and maintain cooler air temperatures than design weather conditions. Since a constant supply air temperature is required for humidity control, more energy may be used during moderate weather conditions. As a result CAV systems consume more fan power, more heating energy, and more cooling energy. The conventional method of reducing energy consumption is to install variable frequency drives (VFDs) on the supply and return air fans. We assume that VFD installation can reduce the fan power consumption up to 10%.

Unitary Equipment represents a majority of the small commercial and school HVAC markets. While high efficiency units are available (SEER 14-15), the majority of this equipment consists of constant volume compressors and fans. Most packaged units in the 7-1/2 ton to 20 ton range have multiple stages of compression (typically 2). Since these units are sized for peak conditions, significant savings are possible by improving part load operations via staging compressors and utilizing variable-speed indoor fans.

A constant volume HVAC unit supplies constant airflow with variable temperature to provide temperature control. In the cooling mode, to meet ventilation requirements, the fan operates continuously and the compressor cycles on and off to meet the space cooling load. The on/off nature of the constant volume unit causes the temperature to constantly fluctuate above and below the room temperature set point temperature.

Single zone VAV, or single zone variable air volume, is an HVAC application in which the HVAC unit varies the airflow at constant temperature to provide space temperature control. In a single zone VAV unit, the controls are upgraded to control a variable speed fan's delivery of airflow provided to the space by modulating the fan motor speed based on the difference between the actual space temperature and the temperature set point. The temperature of the supply air leaving the unit is used to determine how many compressors should operate to maintain the supply air temperature set point.

Chiller Plant Optimization:

This involves identifying the part load performance of each piece of central chiller plant equipment (e.g. chillers, tower fans, pumps) and determining an operational sequence to best fit these pieces together to minimize overall energy consumption. We assume that this optimization can result in up to 5% increase in the chiller plant efficiency.

Optimized (variable speed) Pumping:

Like chiller plant optimization, this measure involves optimizing pump scheduling & VFDs for improved water distribution efficiency. We assume that this optimization can result in up to (10-15%) 37% reduction in the overall pump power.

Need to confirm chiller is compatible and convert AHU's to two-way valves from three-way valves (eliminate bypasses in the system).

Tankless Water Heating:

Tankless water heaters also known as Instantaneous or Demand Water Heaters, heat water directly to provide service hot water as needed (without the use of a storage tank). Therefore, they avoid the standby heat losses associated with storage water heaters. Such systems can be either electric or gas-fired. Compared to conventional system, tankless water heating can reduce the service hot water load by around 37%.

Two Stage Absorption Chillers (substantial change – steam or gas piped):

The energy efficiency of absorption can be improved by recovering some of the heat normally rejected to the cooling tower circuit. A two-stage or two-effect absorption chiller accomplishes this by taking vapors driven off by heating the first stage concentrator (or generator) to drive off more water in a second stage. Two-stage absorption chillers are typically driven by high-pressure steam, direct-fired with natural gas or fuel oil, or using hot exhaust gas from combustion engines. We assume that two-stage system is applicable, only if there is an existing single stage and can lead to 20% increase in its efficiency.

Condensing Boiler:

A condensing boiler utilizes the latent heat of water produced from the burning of fuel, in addition to the standard sensible heat, to increase its efficiency.

Relatively inexpensive, switching out an existing high mass boilers. Utilize hot water reset and operate at lower hot water temperatures to get similar benefits to an instantaneous water heater by controlled heating of smaller volumes of water in line with demand. They match the efficiency of high mass boilers in peak demand, with greater efficiency when the demand is lower.

Steam boilers can also be replaced with condensing boilers and the same part load benefits can be leveraged.

Ground Source Heat Pump:

GSHP is a central heating and/or cooling system that pumps heat to or from the ground. It uses the earth as a heat source (in the winter) or a heat sink (in the summer). This design takes advantage of the moderate temperatures in the ground to boost efficiency and reduce the operational costs of heating and cooling systems. In case building is either cooling or heating dominated, and GHX is used alone needs to be oversized. Over period of several years, this imbalance of heating/cooling rejection can modify the thermal properties of the ground locally, and reduce the efficiency of GSHP. To avoid this detrimental effect, GSHP can be combined with auxiliary cooling and heating system.

Natural Ventilation for night-time pre-cooling:

The concept of nighttime NV for pre-cooling is exactly same as fan assisted nighttime pre-cooling. However, instead of fan, flow induced by NV is used to purge the hot air out of the building. Based on formulation in previous section, the purge time due to NV can be computed as:

$$\sqrt{\left(\frac{}{}\right)}$$

We assume that once the hot inside air has been purged, ambient conditions prevail inside the building. Again, in order to avoid excess cooling or adding moisture, the nighttime NV for pre-cooling is enabled only during favorable conditions, as listed in fan assisted nighttime pre-cooling section.

Use the Airside Economizer energy saving strategy to implement a nighttime building flush and pre-cool in the overnight unoccupied hours. An hour or two of fresh outside air in the early morning provides additional free cooling. Nighttime pre-cooling can mean the office is cool when people arrive for work, but will heat up to normal temperatures with the normal activities of the occupants. Savings can be realized by not having to run mechanical refrigeration for the initial period of the work day.

Direct/Indirect Evaporative Cooling:

Evaporative cooling is a process by which moisture is added to air in order to reduce air temperature and increase relative humidity. Lower the relative humidity, the greater the cooling effect that is possible when moisture is added. The arid climates make them excellent locations for evaporative cooling. In more humid locations, evaporative cooling may be used in dry weather, but will need to be supplemented by conventional cooling in hot, humid weather.

Direct evaporative cooling is the term applied to comfort-cooling applications that simply add moisture directly to an airstream to cool the air while increasing its relative humidity. Direct evaporative cooling, commonly used with residential systems, cools the air by evaporating water to increase the moisture content of the air. Standard residential systems use evaporative media of shredded aspen fibers, typically 1 to 2 inches thick. These systems have an effectiveness of 55 to 70 percent.

Indirect systems cool air without adding moisture; rather indirect evaporative process cools air or water on one side of an impermeable heat-exchange surface such as a thin plastic plate or tube. They are more expensive and use more energy than direct systems, but they can provide energy efficiency in applications where direct evaporative cooling may not be practical. Two-stage systems place an indirect cooling section on the upstream side of a direct cooling stage.

Indirect evaporative cooling uses an air to air heat exchanger to remove heat from the primary air stream without adding moisture. In one configuration, hot dry outside air is passed through a series of horizontal tubes that are wetted on the outside. A secondary air stream blows over the outside of the coils and exhausts the warm, moist air to the outdoors. The outside air is cooled without adding moisture as it passes through the tubes. Indirect evaporative cooling typically has an effectiveness of 75%.

Solar Water Heating and Waste Heating:

Solar water heating (SHW) is one of the most mature renewable energy technologies. There are two main categories of solar water heating systems: Passive systems rely on convection or heat pipes to circulate water or heating fluid in the system, while active systems use a pump. In addition, there are a number of other system characteristics that distinguish different designs: type of collector, location of the collector - roof mount, ground mount, wall mount, location of the storage tank in relation to the collector and method of heat transfer - open-loop or closed-loop (via heat exchanger).

Dessicant Dehumidification:

This ECM involves using a molecular sieve, desiccant-based heat wheel technology that provides sensible and latent energy recovery with a very low level of cross contamination between the incoming outdoor air and the exhaust system discharge.

Desiccant-based systems are more economical than refrigeration systems at lower temperatures and lower moisture levels. Typically, a desiccant dehumidification system is utilized for applications below 45% RH down to 1% RH. Thus, in many applications, a DX or chilled water pre- cooling coil is mounted directly at the dehumidifier inlet. This design allows for removal of much of the initial heat and moisture prior to entering the dehumidifier where the moisture is reduced even further.

In some cases, the use of a desiccant-based system can reduce the operating costs of the existing cooling-based system. For example: When treating ventilation air in building HVAC systems, the dehumidification of the fresh air with the desiccant-based system decreases the installed cost of the cooling system and eliminates deep coils with high air and liquid-side pressure drops. This saves considerable fan and pump energy as well.

Energy Recovery (Enthalpy Wheel):

Energy Recovery: In this principle heat wheels are used for extracting heat and moisture between exhaust air stream and inlet air stream.

Enthalpy wheels, or rotary heat exchangers, transfer sensible or sensible and latent energy between the exhaust air and the incoming outside air. The supply and exhaust streams must be located next to each other. Both sensible-only wheels and total energy wheels, sometimes referred to as desiccant wheels, are available. A total energy wheel can have a sensible and latent effectiveness as high as 75%, which results in a total effectiveness of 75%. Control of the wheel at part loads is accomplished by varying the speed of the wheel, or using a bypass duct, or both.