Comparative Analysis of Benchmarking and Audit Tools

by

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ABSTRACT

Among the various end-use sectors, the commercial sector is expected to have the second-largest increase in total primary energy consumption from 2009 to 2035 (5.8 quadrillion Btu) with a growth rate of 1.1% per year, it is the fastest growing end-use sectors. In order to make major gains in reducing U.S. building energy use commercial sector buildings must be improved.

Energy benchmarking of buildings gives the facility manager or the building owner a quick evaluation of energy use and the potential for energy savings. It is the process of comparing the energy performance of a building to standards and codes, to a set target performance or to a range of energy performance values of similar buildings in order to help assess opportunities for improvement.

Commissioning of buildings is the process of ensuring that systems are designed, installed, functionally tested and capable of being operated and maintained according to the owner's operational needs. It is the first stage in the building upgrade process after it has been assessed using benchmarking tools. The staged approach accounts for the interactions among all the energy flows in a building and produces a systematic method for planning upgrades that increase energy savings.

This research compares and analyzes selected benchmarking and retrocommissioning tools to validate their accuracy such that they could be used in the initial audit process of a building. The benchmarking study analyzes the Energy Use Intensities (EUIs) and Ratings assigned by Portfolio Manager and Oak Ridge National Laboratory (ORNL) Spreadsheets. The 90.1 Prototype models and

Commercial Reference Building model for Large Office building type were used for this comparative analysis. A case-study building from the DOE - funded Energize Phoenix program was also benchmarked for its EUI and rating. The retrocommissioning study was conducted by modeling these prototype models and the case-study building in the Facility Energy Decision System (FEDS) tool to simulate their energy consumption and analyze the retrofits suggested by the tool.

The results of the benchmarking study proved that a benchmarking tool could be used as a first step in the audit process, encouraging the building owner to conduct an energy audit and realize the energy savings potential. The retrocommissioning study established the validity of FEDS as an accurate tool to simulate a building for its energy performance using basic inputs and to accurately predict the energy savings achieved by the retrofits recommended on the basis of maximum LCC savings.

DEDICATION

Thank you, Ma and Papa…

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I would like to express my sincere gratitude to Professor T. Agami Reddy, my thesis Chair, for all his support and constant encouragement throughout the thesis and my academic career at Arizona State University. I am grateful to him for giving me the opportunity to work for the Energize Phoenix project which helped me conceptualize this research project.

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Chapter 1

INTRODUCTION

1.1 Overview

According to US Energy Information Administration (US EIA), the total primary energy use consumption in the United States is estimated to grow at a rate of 0.7% per year from 2009 to 2035 to 114.2 quadrillion Btu in 2035. When classified into residential, commercial, transportation and industrial sectors, the largest increase, 7.2 quadrillion Btu from 2009 to 2035, is in the industrial sector, which was the end-use sector most severely affected by the economic downturn in 2009. When 2008 is used as the base year, the total increase in industrial energy consumption is only about one-half the increase from 2009 to 2035, at 3.3 quadrillion Btu from 2008 to 2035. The second-largest increase in total primary energy consumption from 2009 to 2035 (5.8 quadrillion Btu) is in the commercial sector, which currently accounts for the smallest sectoral share of primary energy use. The growth rate for commercial energy use, at 1.1 percent per year, is the fastest rate among the end-use sectors (US EIA, 2011).

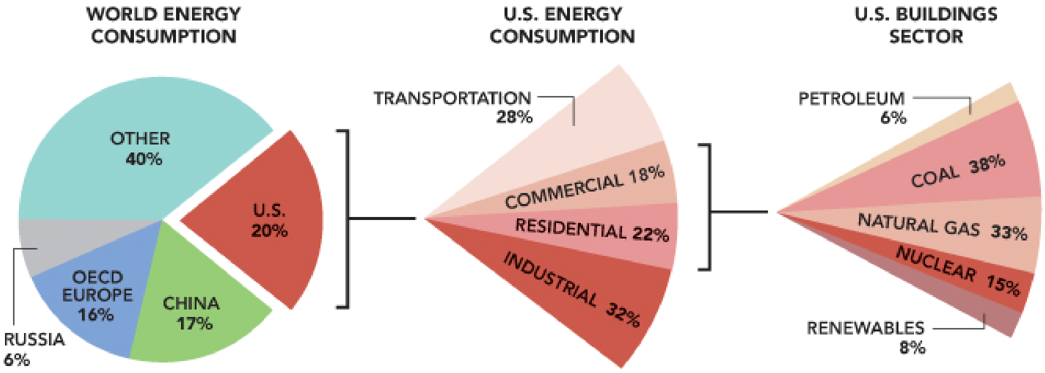


Figure 1: Building Sector Energy Consumption

Commercial sector buildings must be targeted for improvement to make major gains in reducing U.S. building energy use.

Energy benchmarking offers initial building energy performance assessment without rigorous evaluation. It is the process of comparing the energy performance of a particular commercial building to a range of energy-performance values of similar buildings, and helps assess opportunities for improvement and quantifying/verifying energy savings. Just as Energy Guide labels on appliances indicate where the labeled appliance fits into the range of similar appliances from most to least efficient; benchmarking creates a ranking system for buildings. The energy-related building codes, as well as various building-rating organizations, specify and rate the design of buildings. However, these design-based ratings are merely assumptions, while benchmarking rates buildings based on measured energy consumption.

To compare existing buildings of a certain type, one must normalize the energy-usage data. **Normalization** is the process of factoring data using related elements that strongly affect usage. The simplest way to normalize annual energy usage is to divide it by the building's occupied floor area. Common benchmarks are annual kilowatt-hours per square foot and annual thousands of British Thermal Units (Btu) per square foot. One can also use number of workers or units of production to normalize benchmarking data. For example, a printing company can compare energy use per printed page with other printers, for cars one uses miles per gallon, for lighting efficiency one uses lumens per watt, for cooling equipment efficiency we use kW/ton. Similarly, hotels and motels often express their annual energy usage per bed.

One reason design-based ratings are not specific is because the designers do not want to be responsible for the behavior of operators and occupants. The most prominent energy problem noted by commercial energy auditors is that loads are not turned off when not in use. The benchmarking measurement specialists observed that energy award-winning buildings often have high energy bills.

Building commissioning is a method of risk reduction for new construction and major renovation projects to ensure that building systems meet their design intent, operate and interact optimally. This systematic process typically includes building HVAC, controls, lighting, hot water, security, fire and life and safety systems. **Retro-commissioning** (RCx) is a systematic, documented process that identifies low-cost operational and maintenance improvements in existing buildings and brings the buildings up to the design intentions of its current usage (State of California, 2010).

As of 2010, the total U.S. building stock is approximately 275 billion square feet. During normal economic times, approximately 1.75 billion square feet of buildings are torn down each year. Every year, approximately 5 billion square feet is renovated. Every year, approximately 5 billion square feet is newly constructed. By the year 2035, approximately three-quarters (75%) of the built environment will be either new or renovated, representing a historic opportunity for the architecture and building community to reduce its energy consumption (Architecture 2030, 2010).

1.2 Research Outline

Several benchmarking tools have been developed with the intent of assessing energy saving potential without having to perform rigorous evaluation. “Seeing” that a building uses more energy than 80 – 90% of similar buildings can be a convincing indicator for building improvements. The problem with benchmarking tools is that few exist, and for those that do, reliability is uncertain (Sharp, Energy Benchmarking in Commercial Office Buildings, 1996).

This research compares and analyzes selected benchmarking tools such that one of them could be used as the first step in the audit process for retrofit projects. It also explores the usefulness of retrofit/retrocommissioning software as the next step in the audit process to identify pertinent retrofit measures.

The city of Phoenix was awarded a $25 million federal grant from the U.S. Department of Energy Better Buildings Program and the American Recovery and Reinvestment Act (ARRA) to launch, in partnership with Arizona State University and Arizona Public Service, "Energize Phoenix," a project that will save energy, create jobs and transform a diverse array of neighborhoods along a 10-mile stretch of the light rail line (Energize Phoenix, 2010).

The Energize Phoenix program aims to achieve the following specific goals:

- Shrink home energy consumption by up to 30%
- Reduce commercial energy use by up to 18%
- Eliminate carbon emissions by as much as 50,000 metric tons per year
- Upgrade approximately 2,000 homes and 30 million square feet of office and industrial space for greater energy efficiency.

The benchmarking and retrofit/retrocommissioning tools could prove to be useful for analyzing the different retrofit projects for the Energize Phoenix program and thereby help reach the intended goals of the program.

1.3 Scope and Limitations

This research has been carried out using the 90.1 Prototype Building Models, developed by the Pacific Northwest National Laboratory (PNNL) in support of DOE's Building Energy Codes Program (BECP) for large office buildings. This effort is being led by various organizations such as the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) for developing standards such as ASHRAE 90.1 – 2004, ASHRAE 90.1 – 2007, ASHRAE 90.1 – 2010 and the Commercial Reference Building prototype for large office building by the Lawrence Berkeley National Laboratory (LBNL). This research is limited to the large office building prototype which thus could be extended to other building typologies in future studies.

Further, this research evaluates only a limited number of benchmarking and retrofit/retrocommissioning tools due to a lack of commercial availability of other tools described in Chapter 2.

1.4 Targeted Users

The usefulness of this research is primarily targeted at building energy contractors/auditors. It would allow them to conveniently assess the energy use details of the customer and help identify retrofit measures while taking into consideration the cost-effectiveness of each of these recommendations and quantify the associated energy savings. Moreover, it would also help customers assess their energy use as compared to their peers and assist in evaluating and identifying opportunities for improvement and quantifying/verifying energy savings.

1.5 Structure

This thesis has been organized as follows: Chapter 1 gives an introduction to the research topic alongwith the research intent, targeted users and the scope and limitations of the research. Chapter 2 and Chapter 3 elaborate on the various benchmarking and retrofit/retrocommissioning tools that are available and that are used for the purpose of this research. Chapter 4 describes the methodology adopted to analyze both the benchmarking and the retrofit/retrocommissioning tools separately. It also gives a brief description of the various prototype models that have been used for this thesis. Chapter 5 analyzes the results obtained by using the selected benchmarking and retrofit/retrocommissioning tools on the described prototypes and case-study buildings. Chapter 6 summarizes the outcomes of this research and outlines the potential future research directions.

Chapter 2

ENERGY BENCHMARKING

2.1 Overview

Energy use benchmarking is the process of either comparing the energy use of a building or a group of buildings with other similar structures. It informs organizations about how and where they use energy and what factors drive their energy use. Benchmarking enables energy managers to determine the key metrics for assessing performance, to establish baselines and to set goals for energy performance. Uses of energy benchmarking as applied to buildings include:

- Determining how a building's energy use compares with that of others.
- Setting targets for improved performance and tracking progress/persistence.
- Facilitating assessment of property value and marketing rental properties.
- Gaining recognition for exemplary achievement.
- Identifying energy saving strategies.
- Providing reference points for commissioning and retro-commissioning.
- Improving energy demand forecasts (at a range of geographic scales).
- Providing feedback for design of better buildings (via design guidelines, standards, etc.) (Mills, Mathew, & Piette, Action-oriented Benchmarking: Concepts and Tools, 2008).

There exist several different methods for measuring the energy performance of commercial buildings. From simple to complex, these methods range from basic energy consumption benchmarking, to engineering audits and analysis, to more sophisticated computer modeling and simulation. While each approach adds valuable information to understanding the whole-building performance, all have significant shortcomings in their practical utility (Neida & Hicks, 2001).

One of the simplest methods, the annual per square foot benchmarking, provides a quick and cost-effective method to measure energy performance of a building as compared to its regional or national peers. However, certain important variables such as weather, climate, occupancy and operating conditions might be overlooked in this type of evaluation (Komor, 1998). Moreover, expressing a benchmark in terms of typical energy use intensity (kW or kBtu/ft^{2}yr) could be confusing for non-technical management personnel. It could also be misleading as to whether it is being expressed in terms of site energy or source energy (Neida & Hicks, 2001).

Complex approaches such as engineering assessments or computer modeling and simulation generate an elaborate measure of a building's energy performance, but only against itself or against a design standard such as California Title 24 or ASHRAE 90.1. This method of a building's energy performance measurement is debatable because of two reasons: 1) Benchmarking a building against itself gives a baseline indication of the building's current performance as compared to where it could be, but it does not compare its energy performance to other similar buildings. 2) Benchmarking a building against building codes provides a better comparative power but cannot be standardized as the performance baseline could vary according to the modeler's interpretation of the building codes or standards. In addition, other drivers of energy consumption, not controlled by building codes or standards, such as thermal massing, building orientation, plug loads, etc. enlarges the gap between the actual performances of the building and its anticipated performance against the code (Johnson, 2002).

2.2 Energy Benchmarking Tools

Different benchmarking tools assess the energy performance of a building using different methods. Some of these tools have been described in detail as follows.

2.2.1 ASHRAE Building Energy Quotient (Building EQ)

ASHRAE Building EQ is a building energy labeling program which provides the general public, current and potential building owners and tenants, and building operations and maintenance staff with information on the potential and actual energy use of buildings.

- It helps building owners and operators to assess how their building compares to peer buildings, and establish a measure of their potential for energy performance improvement.
- Building owners can use the information provided to differentiate their building from others to attract potential buyers or tenants.
- Potential buyers or tenants can gain insight into the value and potential long-term cost of a building.
- Operations and maintenance staff can use the results to inform their decisions on maintenance activities and influence building owners and managers to pursue equipment upgrades and demonstrate the return on

> investment for energy efficiency projects (ASHRAE BEQ Program, 2009).

New buildings are eligible to receive an asset rating, which is called the "As Designed" rating for the Building EQ label and certificate. An operational rating will be available once the building has at least one year of data of the actual energy use of the building. The operational rating is called the "In Operation" rating on the Building EQ label and certificate. Existing buildings are eligible to receive both an asset and an operational rating.

The Asset (As Designed) rating provides an assessment of the building based on the components specified in the design—including mechanical systems, building envelope, orientation, and daylighting. The asset rating is based on the results of a field inspection and a building energy model.

The Operational (In Operation) rating provides information on the actual energy use of a building and is based on a combination of the structure of the building and how it is operated. Information learned through subsequent years of operational labels can provide building owners and operations and maintenance staff with valuable insight into how the building performs, opportunities for improvement, and where similar buildings fall in comparison. It also provides a means for owners of portfolios of several buildings to identify priorities for energy savings investment (ASHRAE Building Energy Labeling Program Implementation Committee , 2009)

Table 1: Comparison of Operational and Asset Ratings

(ASHRAE Building Energy Labeling Program Implementation Committee , 2009)

Operational Rating - "In Operation"	**Asset Rating - "As Designed"**
• Objective is to improve operations	• Objective is to value property
• Rating based on measured energy usage, adjusted for weather	• Rates the building, not the occupancy and operation.
• No inherent requirement for field verification	• Focus is on the physical building characteristics and permanent energy systems
• Ratings sometimes adjusted based on levels of service	• Differences in operational behavior are ignored
• Good for use in existing building energy efficiency incentive programs	• Rating is derived from a model-based estimate of energy usage, compared to a stock median or building code baseline for the building type
• Good for managing building portfolios over time	• Field verification is a requirement
• Example: U.S. EPA's ENERGY STAR® Portfolio Manager	• Good for valuing building performance within a financial transaction
	• A basis for energy efficiency code compliance and beyond code new construction incentive programs.
	• Examples: RESNET and CEC Home Energy Rating Systems

Two types of rating scales are generally used for evaluating building energy performance. Statistical methods use a frequency distribution of the population of buildings represented and rate a building according to its percentile location in the distribution.

Technical rating methods compare a building's energy performance to technical potential reference points where Net Zero Energy performance is zero on the scale and the building type population median is set at 100. The ASHRAE Building EQ is the same basic scale that is used in the European Union for commercial buildings and analogous to the scale used in North America for the residential asset rating system (known as HERS, the Home Energy Rating System). Comparisons of the two rating scales are shown in Table 2 (ASHRAE Building Energy Labeling Program Implementation Committee , 2009).

Table 2: Comparison of Rating Scales

(ASHRAE Building Energy Labeling Program Implementation Committee , 2009)

Statistical Rating Scale	**Technical Rating Scale**
• Fit a regression model to a sample distribution of population data	• Rated buildings compared to stock median or code level of performance
• Existing building population sample used to set low and high end of scale	• Energy policy sets low end of scale (e.g. zero net energy or zero carbon)
• Representative data required for the entire distribution of existing buildings of a particular type	• Only stock median values are required for existing buildings of a particular type
• Does not necessarily include energy policy goals in rating scale	

The ASHRAE Building EQ Rating

The Building EQ rating is the ratio of energy use of the rated building to the median energy use of its building type. Energy use is expressed as source energy EUI, or source Btus per square foot per year. The best energy performance on the Building EQ is Net Zero Energy with a rating of zero. The median of building performance for that particular building type is set at 100. While there is no theoretical upper end to the scale to track poor energy performance, in this version of the Certificate, the upper limit is set at a Building EQ rating of - Poor - for any score of 125 or greater. Net Zero Energy buildings that also produce an energy surplus can have a rating of less than zero. The ASHRAE Building EQ scale is illustrated in Figure 2 along with the Building EQ label (Figure 3).

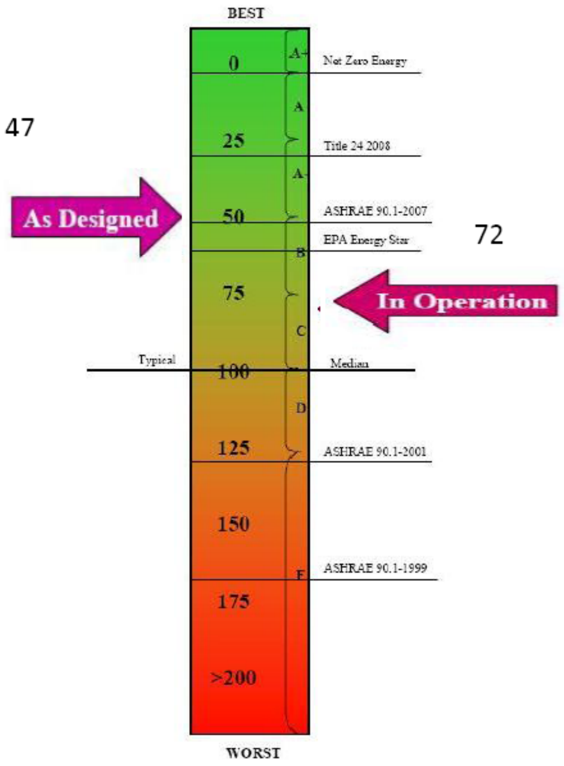


Figure 2: ASHRAE Building EQ Scale

(ASHRAE Building Energy Labeling Program Implementation Committee , 2009)

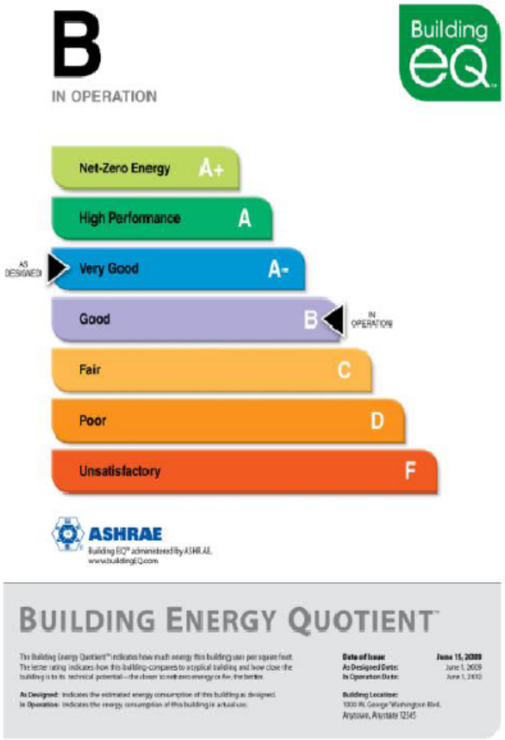


Figure 3: ASHRAE Building EQ Label

(ASHRAE Building Energy Labeling Program Implementation Committee , 2009)

Thus, buildings in the Building EQ program will be compared to a scale that is tied to net-zero energy use and energy use for the building type as obtained from Energy Star data, which is in turn based on Commercial Building Energy Consumption Survey (CBECS) data.

2.2.2 EnergyIQ

EnergyIQ, developed by Lawrence Berkeley National Laboratory (LBNL), is an action-oriented energy benchmarking tool for non-residential buildings which provides both an assessment of the existing energy use and also provides a list of opportunities and recommendations for cost effective investments. The benchmarking methods, visualizations, and user interface design are determined on the basis of an end-user needs assessment survey and best-practice guidelines from ASHRAE. EnergyIQ represents a major advancement beyond LBNL's previous CalArch tool, which provided web-based whole-building benchmarking based upon an earlier version of the California End Use Survey (CEUS).

Action-oriented benchmarking is intrinsically more in-depth than conventional whole-building benchmarking, essentially forming a bridge between full-fledged simulation (for design) and energy audits (for retrofit), as shown in Figure 4. An action-oriented benchmarking process ideally interoperates with other aspects of building energy management, particularly commissioning and retro-commissioning, where results can help identify deficiencies and suggest where interventions are merited (Mills, Mathew, & Piette, Action-oriented Benchmarking: Concepts and Tools, 2008).

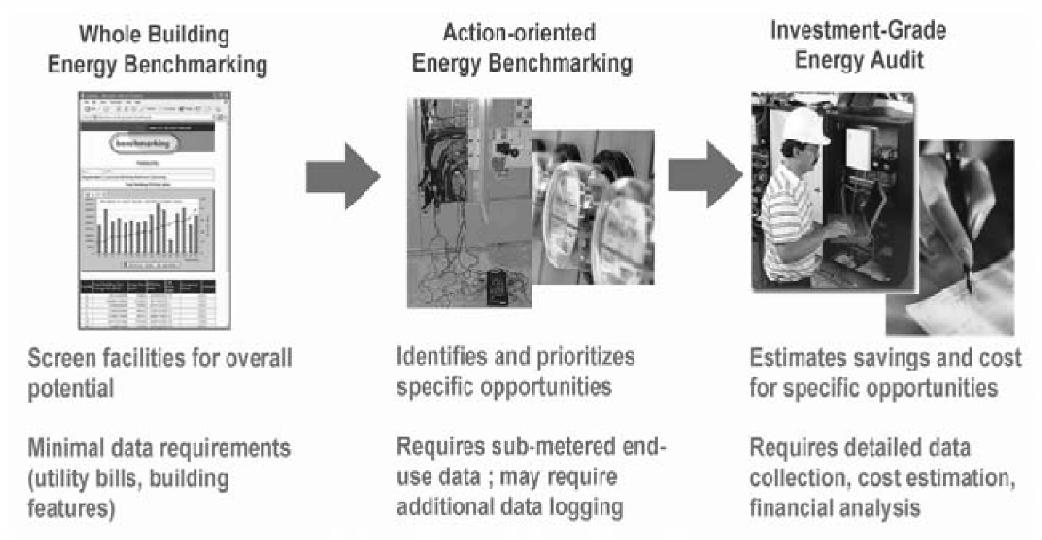


Figure 4: Action-orientated benchmarking in context of conventional benchmarking and energy audits.

(Mills, Mathew, & Piette, Action-oriented Benchmarking: Concepts and Tools, 2008)

Action-oriented benchmarking enables users to identify potential energy efficiency options and prioritize areas for more detailed analysis and full-scale audits. This represents a means of opportunity assessment not afforded by conventional benchmarking.

EnergyIQ has been designed to meet user needs identified in a survey carried out by LBNL and the outcomes of the ASHRAE Technical Research Project-1286 best practices protocol for energy benchmarking tool design (Glazer, 2006). Most of these outcomes have been incorporated in the design of EnergyIQ.

The user can filter the data at any point by building type (62 options), location, vintage, floor area, and/or size. The user can describe portfolios of buildings and evaluate them individually or in aggregate. The tool accommodates the CBECS database in addition to CEUS database, and the user has the option to include them as peer groups (as well as the results from other users of the tool) against which to compare their own buildings (Mills, Mathew, & Piette, Action-oriented Benchmarking: Concepts and Tools, 2008).

Benchmarking—particularly if action-oriented—is integral to the process of identifying opportunities and motivating decision-makers to implement measures that improve the energy performance of buildings. EnergyIQ represents a new generation of tools for increasing the role of benchmarking in this broader process.

Table 3: Condensed summary of ASHRAE TRP-1286 best practice energy benchmarking tool design

(Mills, Mathew, & Piette, Action-oriented Benchmarking: Concepts and Tools, 2008)

Focus on energy (vs. other resources) *	Provide weather normalization to allow for multi-year trending *
Emphasis on ease-of-use for non-technical building owners and operators *	Include recommendations *
Adopt a clear goal during tool development *	Limit to one input page; one result page *
Use empirical building survey data to define peer groups *	Provide user accounts with saved data *
Make it easy to update and add new data *	All major browsers supported *
Distinguish among building types *	Portfolio option for multiple buildings *
Use multiple regression plus 'smoothing' *	Optional batch upload (FTP, etc.) *
Account for location/climate dependency *	Ability to combine multiple buildings *
Publicly document the rating method *	Utility data; upload *
Tool should be web-based with minimal inputs, eg. Monthly consumption, building type, floor area, location *	Link to utility program information *
Use a scale from 0 to 100 percent to bin results of peer group	Provide on-line 'how to use' training *
Provide simple graphical output, like appliance labels *	Longitudinal benchmarking over time *
Use histograms for deeper (optional) analysis *	Can be statically integrated into utility websites *
Available at no cost to users *	Give additional points for 'environmental criteria'
Link to simulation-based design compliance with ASHRAE standard	Certification program, based on tool
Limit rating to energy, as opposed to comprehensive environmental indicators *	Consistent floor-area definition *
Include CO_2 emissions *	

* Included in EnergyIQ

2.2.3 ORNL Spreadsheet Tool

The Energy Use Intensity (EUI) distributions used in the spreadsheets developed by Oak Ridge National Laboratory (ORNL) were based upon a statistical analysis of approximately 1500 office buildings in the US Energy Information Administration's 1992 CBECS database. These were divided into their corresponding nine US census divisions for analysis. Thus, different areas of the US could have different results depending on what characteristics were found most important to the locale. A subset of over 70 building characteristics from the CBECS database were selected and examined for their relationship to office building energy use. These were refined down to four characteristics that were the most important determinants of electricity use and the four most important ones for non-electric energy use. These few characteristics explained most of the variations in energy use that could be explained by considering all characteristics that had statistically significant relationships to energy use. Thus, addressing additional characteristics provided limited value. Within census divisions, climate was not a major driver of either electric or non-electric energy use (Sharp, Energy Benchmarking in US Office Buildings, 1996).

The benchmarking spreadsheets developed by ORNL allow one to identify where one's specific office building ranks relative to others. They calculate the energy use intensity of the building, provide the typical (median) EUI for office buildings with the same characteristics as yours, and identify where the building's performance ranks compared to others. They go beyond the customary normalization by floor area and account for performance differences due to variations in worker density, the number of personal computers, operating hours, occupancy type, and heating fuel types. Beyond floor area, these characteristics were found to be the most common and most important drivers of electric and non-electric energy use in US office buildings. Climate impacts on energy use were less significant, in part because analyses were conducted within regional census divisions (Sharp, Energy Benchmarking in US Office Buildings, 1996).

In this approach, the building is compared to others that have the same characteristics you provide as input. Thus, one is not comparing the building, which may have a high worker density (an important driver of energy use in 7 of 9 census divisions), to others with medium or low worker densities. Other important drivers of energy use are also accounted for. Wide variances in these drivers can strongly impact the energy use in office buildings. By accounting for these, comparing office buildings that have sound reasons for higher energy use to those that do not is avoided. Average EUIs, although very commonly used, can be very misleading. This occurs because the distribution of energy use intensities for a group of buildings is normally highly skewed. This causes the average EUI for a group to be much higher than the median. For this situation, 65 to 70% or more of the buildings in many groups will often have lower EUIs than the group average. Many inefficient buildings will appear as moderate users in this situation. Small sample sizes can magnify this problem.

ORNL has also developed a brief table which acts as an indicator of potential savings in the building after benchmarking the building using these spreadsheets.

Table 4: Energy Use and Cost Reduction Potential (%)

(Buildings Technology Center - ORNL, 1996)

Rating for your building	**Energy use and cost reduction potential (%)**	**Walk-thru energy assessment recommended?**
below 20%	above 50%	Definitely
20 to 40%	35 to 50%	Yes
40 to 60%	20 to 35%	Maybe
above 60%	below 25%	No

Due to fuel cost differences and differing rate schedules, energy cost reduction percentiles should not be expected to exactly match energy use reduction percentiles. If a large portion of the energy costs consist of electric demand charges (often they make up 30-50% of a customer's electricity bill), the difference between energy use reduction percent and energy cost reduction percent can be significant.

2.2.4 Portfolio Manager

ENERGY STAR's Portfolio Manager has been developed with a joint effort between the US Environmental Protection Agency (US EPA) and US Department of Energy (US DOE). It is a free online software tool for tracking energy and water use and rating the energy performance of selected building types. The tool enables users to:

- Track multiple energy and water meters
- Benchmark facilities relative to past performance
- View percent improvement in weather-normalized source energy
- Monitor energy and water costs

- Verify building energy performance
- Determine energy performance ratings

For many building types, Portfolio Manager can provide an EPA energy performance rating. EPA's national energy performance ratings are derived from U.S. energy and facility data, and account for the impact of weather variations and key physical and operating characteristics of each building. Portfolio Manager allows one to rate the energy performance of the building on a scale of 1–100 relative to similar buildings nationwide. Buildings with superior performance are eligible to earn EPA recognition. The ENERGY STAR label is awarded for facilities achieving the top 25 percent of performance ratings nationally, without compromising comfort or services.

Portfolio Manager calculates the building's greenhouse gas emissions (including carbon dioxide, methane, and nitrous oxide) from on-site fuel combustion and purchased electricity and district heating and cooling. Portfolio Manager also enables tracking of avoided emissions from any Renewable Energy Certificates. While the emissions calculations are based on the amount of energy your building consumes, they have no bearing on its energy performance rating. The methodology for calculating greenhouse gas emissions in Portfolio Manager was designed to be consistent with the Greenhouse Gas Protocol developed by the World Resources Institute and World Business Council for Sustainable Development, and is compatible with the accounting, inventory and reporting requirements of EPA's Climate Leaders program, as well as other state and NGO registry and reporting programs (US EPA, 2011).

Annual energy consumption in buildings can vary up to 30% depending on local weather. In evaluating the energy performance of a building, the Energy Performance Rating (EPR) removes the impact of weather by determining what the building's energy consumption would be during a "normal" weather year. This weather normalization is accomplished by regressing one year of monthly energy consumption data against actual outdoor air temperatures. Having characterized the building's energy consumption as a function of outdoor air temperature, this model is driven with a year of 30-year average normal air temperatures (Neida & Hicks, 2001).

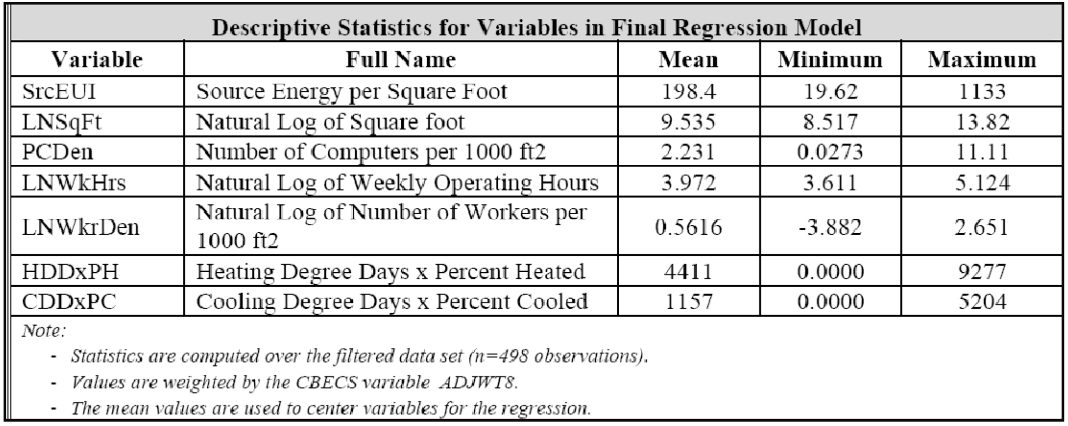
The office regression model is based on data from the Department of Energy, Energy Information Administration's 2003 Commercial Building Energy Consumption Survey (CBECS). Four types of filters are applied to define the peer group for comparison and to overcome any technical limitations in the data: Building Type Filters, EPA Program Filters, Data Limitation Filters, and Analytical Filters. The dependent variable in the office analysis is source energy use intensity (source EUI). This is equal to the total source energy use of the facility divided by the gross floor area. By setting source EUI as the dependent variable, the regressions analyze the key drivers of source EUI – those factors that explain the variation in source energy per square foot in offices.

On the basis of the regression analysis, the following six characteristics were identified as the key explanatory variables in estimating the expected average source EUI (kBtu/ft^2) in offices:

- Natural log of gross square foot
- Number of personal computers (PCs) per 1,000 square feet
- Natural log of weekly operating hours
- Natural log of the number of workers per 1,000 square feet
- Heating degree days times Percent of the building that is heated
- Cooling degree days times Percent of the building that is cooled

Each independent variable is centered relative to the mean value, presented in Table 5.

Table 5: Descriptive statistics for the independent variables
(US EPA, 2007)



Descriptive Statistics for Variables in Final Regression Model

Variable	Full Name	Mean	Minimum	Maximum
SrcEUI	Source Energy per Square Foot	198.4	19.62	1133
LNSqFt	Natural Log of Square foot	9.535	8.517	13.82
PCDen	Number of Computers per 1000 ft2	2.231	0.0273	11.11
LNWkHrs	Natural Log of Weekly Operating Hours	3.972	3.611	5.124
LNWkrDen	Natural Log of Number of Workers per 1000 ft2	0.5616	-3.882	2.651
HDDxPH	Heating Degree Days x Percent Heated	4411	0.0000	9277
CDDxPC	Cooling Degree Days x Percent Cooled	1157	0.0000	5204

Note:

- *Statistics are computed over the filtered data set (n=498 observations).*
- *Values are weighted by the CBECS variable ADJWT8.*
- *The mean values are used to center variables for the regression.*

Example Calculation (US EPA, 2007)

The following is a specific example with the office model:

Step 1 – User enters building data into Portfolio Manager

For the purposes of this example, sample data is provided

- Energy data
    - Total annual electricity = 3,500,000 kWh
    - Total annual natural gas = 4,000 therms
    - Note that this data is actually entered in monthly meter entries.

- Operational data
    - Gross floor area (ft^2) = 200,000
    - Weekly operating hours = 80
    - Workers on main shift = 250
    - Number of personal computers = 250
    - Percent heated = 100
    - Percent cooled = 100
    - HDD (provided by Portfolio Manager, based on zip code) = 4937
    - CDD (provided by Portfolio Manager, based on zip code) = 1046

Step 2 – Portfolio Manager computes the Actual Source Energy Use Intensity

In order to compute actual source EUI, Portfolio Manager must convert each fuel from the specified units (e.g. kWh) into Site kBtu and must convert from Site kBtu to Source kBtu.

- Convert the meter data entries into site kBtu
    - Electricity: (3,500,000kWh)*(3.412kBtu/kWh) = 11,942,000 kBtu Site
    - Natural gas: (4,000 therms)*(100kBtu/therm) = 400,000 kBtu Site
- Apply the source-site ratios to compute the source energy
    - Electricity: 11,942,000 Site kBtu*(3.34 Source kBtu/Site kBtu) = 39,889,280 kBtu Source
    - Natural Gas: 400,000 Site kBtu *(1.047 Source kBtu/Site kBtu) = 418,800 kBtu Source
- Combine source kBtu across all fuels
    - 39,889,280 kBtu + 418,800 kBtu = 40,308,080 kBtu

- Divide total source energy by gross floor area
    - Source EUI = 40,308,080 kBtu/200,000ft^2 = 201.5 kBtu/ft^2

Step 3 – Portfolio Manager computes the Predicted Source Energy Intensity

Portfolio Manager uses the building data entered under Step 1 to compute centered values for each operating parameter. These centered values are entered into the office regression equation to obtain a predicted source EUI.

- Calculate centered variables
    - Use the operating characteristic values to compute each variable in the model.

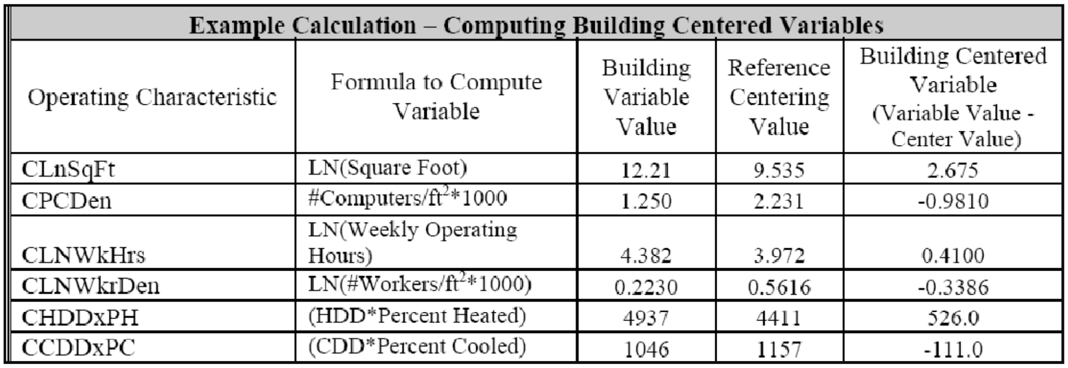
      (e.g. LN(Square Foot) = LN(200,000) = 12.21)

    - Subtract the reference centering value from calculated variable

      (e.g. LN(Square Foot) - 9.535 = 12.21 – 9.535 = 2.675).
    - These calculations are summarized in Table 6
- Compute predicted source energy use intensity
    - Multiply each centered variable by the corresponding coefficient in the model

      (e.g. Coefficient*Centered LN(Square Foot) = 34.17*2.675 = 91.40)
    - Take the sum of these products (i.e. coefficient*Centered Variable) and add to the constant (this yields a predicted Source EUI of 282.9 kBtu/ft^2)
    - This calculation is summarized in Table 7

Table 6: Computing Building Centered Variables



Example Calculation – Computing Building Centered Variables

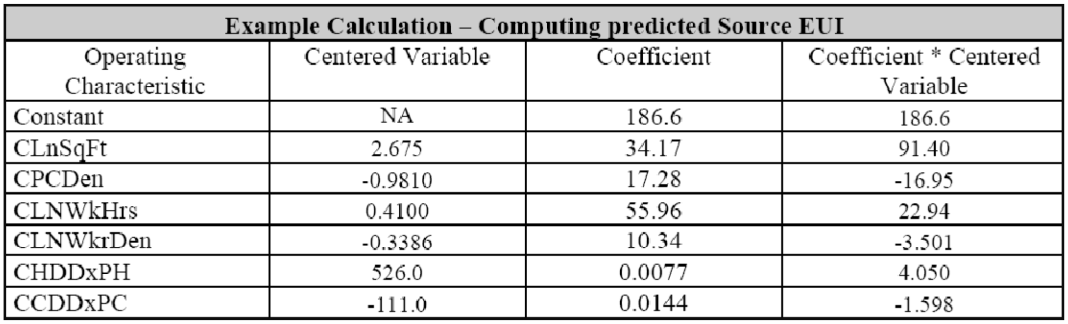
Operating Characteristic	Formula to Compute Variable	Building Variable Value	Reference Centering Value	Building Centered Variable (Variable Value - Center Value)
CLnSqFt	LN(Square Foot)	12.21	9.535	2.675
CPCDen	#Computers/ft^2*1000	1.250	2.231	-0.9810
CLNWkHrs	LN(Weekly Operating Hours)	4.382	3.972	0.4100
CLNWkrDen	LN(#Workers/ft^2*1000)	0.2230	0.5616	-0.3386
CHDDxPH	(HDD*Percent Heated)	4937	4411	526.0
CCDDxPC	(CDD*Percent Cooled)	1046	1157	-111.0

Step 4 – Portfolio Manager computes the energy efficiency ratio

The energy efficiency ratio is equal to: Actual Source EUI/ Predicted Source EUI

- Ratio = 201.5/282.9 = 0.7123

Table 7: Computing predicted Source EUI



Example Calculation – Computing predicted Source EUI

Operating Characteristic	Centered Variable	Coefficient	Coefficient * Centered Variable
Constant	NA	186.6	186.6
CLnSqFt	2.675	34.17	91.40
CPCDen	-0.9810	17.28	-16.95
CLNWkHrs	0.4100	55.96	22.94
CLNWkrDen	-0.3386	10.34	-3.501
CHDDxPH	526.0	0.0077	4.050
CCDDxPC	-111.0	0.0144	-1.598

Step 5 – Portfolio Manager looks up the efficiency ratio in the lookup table

Starting at 100 and working down, Portfolio Manager searches the lookup table (Table 8) for the first ratio value that is larger than the computed ratio for the building.

- A ratio of 0.7123 is less than 0.7218 (requirement for 72) but greater than 0.7119 (requirement for 73)
- **The rating is 72**

When conducting regression analyses and when calculating energy performance ratings in Portfolio Manager, the actual reported energy use intensity and the actual HDD and CDD experienced by the building during the given timeframe are applied. Weather normalized source energy use intensity is not used in determining energy performance ratings (US EPA, 2011).

Table 8: Look-up table for office ratings (US EPA, 2011)

Lookup Table for Office Rating								
Rating	Cumulative Percent	Energy Efficiency Ratio			Rating	Cumulative Percent	Energy Efficiency Ratio	
		> =	<				> =	<
100	0%	0	0.278705		50	50%	0.925442	0.935487
99	1%	0.278705	0.328379		49	51%	0.935487	0.945611
98	2%	0.328379	0.363070		48	52%	0.945611	0.955821
97	3%	0.363070	0.390860		47	53%	0.955821	0.966125
96	4%	0.390860	0.414570		46	54%	0.966125	0.976528
95	5%	0.414570	0.435548		45	55%	0.976528	0.987040
94	6%	0.435548	0.454556		44	56%	0.987040	0.997667
93	7%	0.454556	0.472069		43	57%	0.997667	1.008419
92	8%	0.472069	0.488407		42	58%	1.008419	1.019304
91	9%	0.488407	0.503796		41	59%	1.019304	1.030331
90	10%	0.503796	0.518402		40	60%	1.030331	1.041511
89	11%	0.518402	0.532352		39	61%	1.041511	1.052853
88	12%	0.532352	0.545744		38	62%	1.052853	1.064369
87	13%	0.545744	0.558657		37	63%	1.064369	1.076072
86	14%	0.558657	0.571154		36	64%	1.076072	1.087973
85	15%	0.571154	0.583289		35	65%	1.087973	1.100087
84	16%	0.583289	0.595105		34	66%	1.100087	1.112428
83	17%	0.595105	0.606640		33	67%	1.112428	1.125013
82	18%	0.606640	0.617925		32	68%	1.125013	1.137858
81	19%	0.617925	0.628989		31	69%	1.137858	1.150984
80	20%	0.628989	0.639856		30	70%	1.150984	1.164412
79	21%	0.639856	0.650546		29	71%	1.164412	1.178163
78	22%	0.650546	0.661079		28	72%	1.178163	1.192263
77	23%	0.661079	0.671471		27	73%	1.192263	1.206741
76	24%	0.671471	0.681738		26	74%	1.206741	1.221627
75	25%	0.681738	0.691894		25	75%	1.221627	1.236956
74	26%	0.691894	0.701950		24	76%	1.236956	1.252768
73	27%	0.701950	0.711919		23	77%	1.252768	1.269105
72	28%	0.711919	0.721810		22	78%	1.269105	1.286018
71	29%	0.721810	0.731635		21	79%	1.286018	1.303565
70	30%	0.731635	0.741401		20	80%	1.303565	1.321809
69	31%	0.741401	0.751118		19	81%	1.321809	1.340827
68	32%	0.751118	0.760793		18	82%	1.340827	1.360708
67	33%	0.760793	0.770434		17	83%	1.360708	1.381554
66	34%	0.770434	0.780049		16	84%	1.381554	1.403491
65	35%	0.780049	0.789645		15	85%	1.403491	1.426665
64	36%	0.789645	0.799227		14	86%	1.426665	1.451258
63	37%	0.799227	0.808804		13	87%	1.451258	1.477493
62	38%	0.808804	0.818380		12	88%	1.477493	1.505650
61	39%	0.818380	0.827963		11	89%	1.505650	1.536087
60	40%	0.827963	0.837558		10	90%	1.536087	1.569275
59	41%	0.837558	0.847171		9	91%	1.569275	1.605847
58	42%	0.847171	0.856808		8	92%	1.605847	1.646683
57	43%	0.856808	0.866475		7	93%	1.646683	1.693068
56	44%	0.866475	0.876178		6	94%	1.693068	1.746975
55	45%	0.876178	0.885923		5	95%	1.746975	1.811687
54	46%	0.885923	0.895716		4	96%	1.811687	1.893296
53	47%	0.895716	0.905563		3	97%	1.893296	2.005317
52	48%	0.905563	0.915469		2	98%	2.005317	2.190161
51	49%	0.915469	0.925442		1	99%	2.190161	> 2.190161

Chapter 3

COMMISSIONING OF BUILDINGS

3.1 Overview

Commissioning of buildings is the process of ensuring that systems are designed, installed, functionally tested and capable of being operated and maintained according to the owner’s operational needs. Retrocommissioning is the same systematic process applied to existing buildings that have never been commissioned to ensure that their systems can be operated and maintained according to the owner’s needs. It is the first stage in the building upgrade process after it has been assessed using benchmarking tools. The staged approach accounts for the interactions among all the energy flows in a building (Figure 5) and produces a systematic method for planning upgrades that increases energy savings.

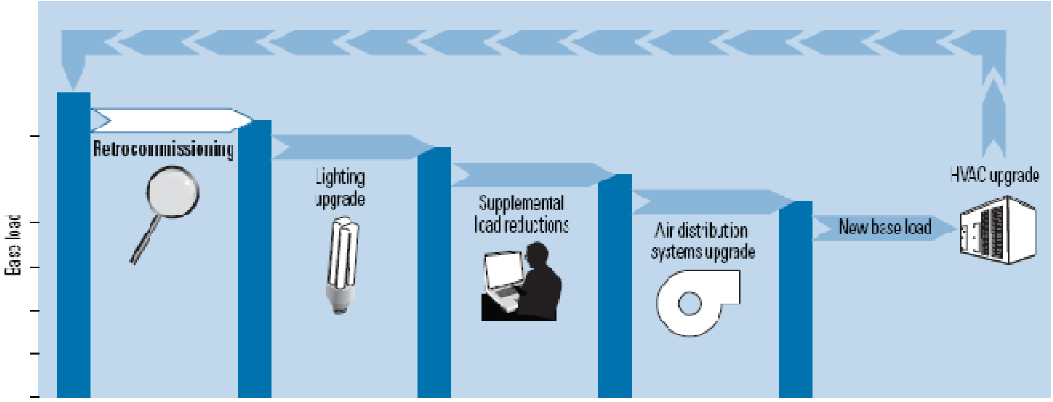
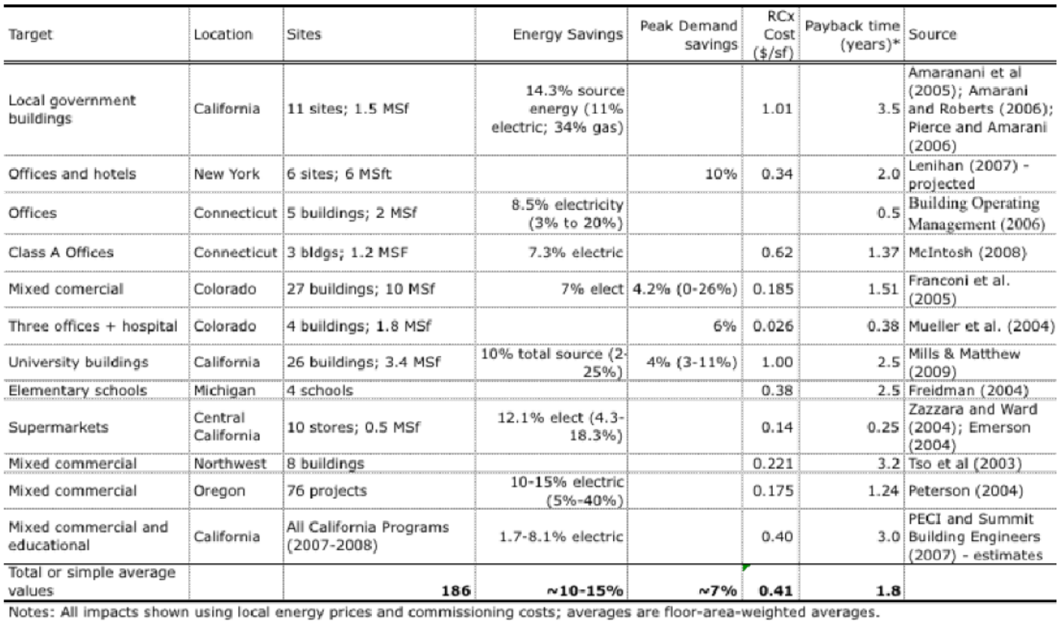


Figure 5: Stages of an integrated upgrade approach
(US EPA, 2008)

Table 9 lists some of the case-studies of large-scale commissioning efforts which demonstrate attractive energy savings and payback times.

Table 9: Examples of existing building commissioning project costs and savings

(Mills, Building Commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions, 2009)



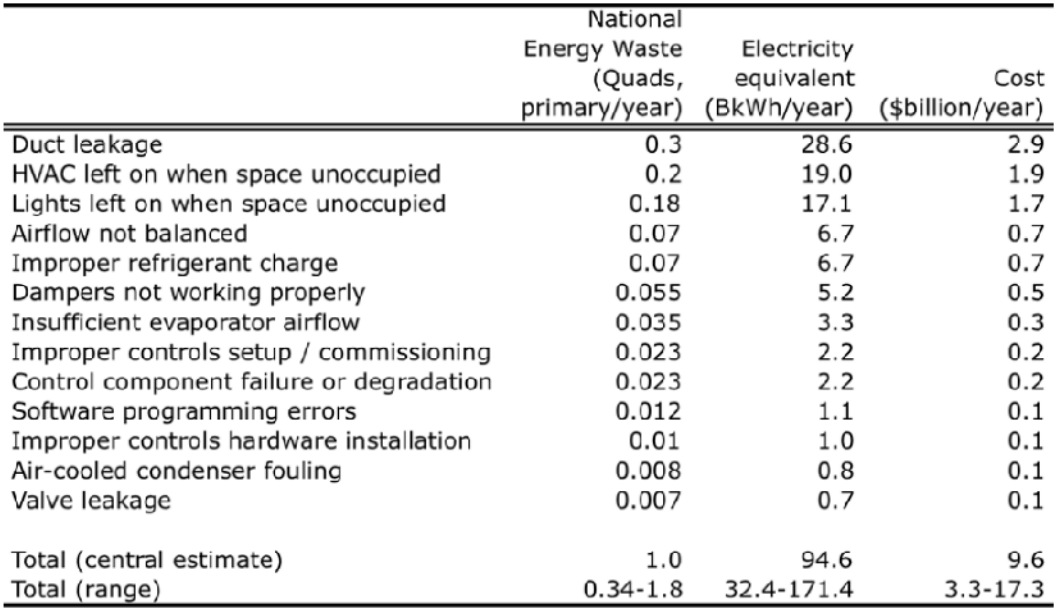
Target	Location	Sites	Energy Savings	Peak Demand savings	RCx Cost ($/sf)	Payback time (years)*	Source
Local government buildings	California	11 sites; 1.5 MSf	14.3% source energy (11% electric; 34% gas)		1.01	3.5	Amaranani et al (2005); Amarani and Roberts (2006); Pierce and Amarani (2006)
Offices and hotels	New York	6 sites; 6 MSft		10%	0.34	2.0	Lenihan (2007) - projected
Offices	Connecticut	5 buildings; 2 MSf	8.5% electricity (3% to 20%)			0.5	Building Operating Management (2006)
Class A Offices	Connecticut	3 bldgs; 1.2 MSF	7.3% electric		0.62	1.37	McIntosh (2008)
Mixed comercial	Colorado	27 buildings; 10 MSf	7% elect	4.2% (0-26%)	0.185	1.51	Franconi et al. (2005)
Three offices + hospital	Colorado	4 buildings; 1.8 MSf		6%	0.026	0.38	Mueller et al. (2004)
University buildings	California	26 buildings; 3.4 MSf	10% total source (2-25%)	4% (3-11%)	1.00	2.5	Mills & Matthew (2009)
Elementary schools	Michigan	4 schools			0.38	2.5	Freidman (2004)
Supermarkets	Central California	10 stores; 0.5 MSf	12.1% elect (4.3-18.3%)		0.14	0.25	Zazzara and Ward (2004); Emerson (2004)
Mixed commercial	Northwest	8 buildings			0.221	3.2	Tso et al (2003)
Mixed commercial	Oregon	76 projects	10-15% electric (5%-40%)		0.175	1.24	Peterson (2004)
Mixed commercial and educational	California	All California Programs (2007-2008)	1.7-8.1% electric		0.40	3.0	PECI and Summit Building Engineers (2007) - estimates
Total or simple average values		**186**	**~10-15%**	**~7%**	**0.41**	**1.8**	

Notes: All impacts shown using local energy prices and commissioning costs; averages are floor-area-weighted averages.

In 2004, Lawrence Berkeley National Laboratory estimated $18 billion per year of potential savings from commissioning throughout the United States (Mills, et al., 2004). Analysis of another study (Westphaler, Feng, Llana, & Quartararo, 2005) published in 2005 suggests a potential savings for the top 13 (of 100) typical commercial building faults alone at $3.3 - $17 billion per year. Table 10 lists the top 13 faults causing energy inefficiencies in commercial buildings.

Table 10: Top faults causing energy inefficiencies in commercial buildings

(Westphaler, Feng, Llana, & Quartararo, 2005)



	National Energy Waste (Quads, primary/year)	Electricity equivalent (BkWh/year)	Cost ($billion/year)
Duct leakage	0.3	28.6	2.9
HVAC left on when space unoccupied	0.2	19.0	1.9
Lights left on when space unoccupied	0.18	17.1	1.7
Airflow not balanced	0.07	6.7	0.7
Improper refrigerant charge	0.07	6.7	0.7
Dampers not working properly	0.055	5.2	0.5
Insufficient evaporator airflow	0.035	3.3	0.3
Improper controls setup / commissioning	0.023	2.2	0.2
Control component failure or degradation	0.023	2.2	0.2
Software programming errors	0.012	1.1	0.1
Improper controls hardware installation	0.01	1.0	0.1
Air-cooled condenser fouling	0.008	0.8	0.1
Valve leakage	0.007	0.7	0.1
Total (central estimate)	1.0	94.6	9.6
Total (range)	0.34-1.8	32.4-171.4	3.3-17.3

Adapted from (Westphaler, Feng, Llana, & Quartararo, 2005) assuming 10,500 Btu/kWh and $ 0.10/kWh

3.2 Retrocommissioning/ Audit Tools

Facility Energy Decision System (FEDS)

The Facility Energy Decision System (FEDS) model is under development at the Pacific Northwest National Laboratory (PNNL) for the Department of Energy's (DOE) Federal Energy Management Program (DOE-FEMP), the U.S. Army Construction Engineering Research Laboratory (USA-CERL), the U.S. Army Forces Command (FORSCOM), the DOE’s Rebuild America Program, the Defense Commissary Agency (DeCA), the U.S. Naval Facilities Engineering Service Center (NFESC), the Tennessee Army National Guard, U.S. Army Installation Management Agency Southeast Region (IMA/SERO), U.S. Coast Guard (USCG) and Public Works and Government Services Canada (PNNL, 2008).

It is a user friendly building energy efficiency software tool for assessing the energy efficiency potential of facilities ranging from single building to multi-building campuses and large federal installations. It quickly and objectively identifies energy efficiency improvements that maximize life-cycle savings. The windows based, menu driven software requires only minimal user experience and input to perform energy efficiency assessment screenings as well as detailed energy retrofit project analyses (PNNL, 2011).

Some of the key features of the software are as follows:

- FEDS requires only minimal user input but is also able to accept detailed building system parameters. It approximates unspecified parameters based on typical characteristics for a building of the specified type, size, age, and location and other details.

- It simulates energy and cost performance of heating, cooling, ventilation, lighting, motors, plug loads, refrigeration, building shell, and hot water systems alongwith central plants and thermal loops.
- It computes energy consumption and fuel demand for each fuel type, technology, end use, building, and the entire installation.
- It provides a comprehensive approach to fuel-neutral, technology independent, integrated energy resource planning and acquisition.
- It assesses thousands of prospective energy efficiency options via a site optimized life-cycle cost minimization process.
- It reports investment requirements, net present value and payback period alongwith pre- and post-retrofit energy consumption and costs and air pollutant emissions impacts.

The FEDS software allows data input to range from minimal to extremely detailed. With minimal input, FEDS can be used as a top-down, first-pass energy systems analysis and energy resource acquisition decision software tool for buildings and facilities. Providing FEDS with more detailed input allows the user to generate optimized building retrofits for an entire installation and provides detailed output for each retrofit in each building set.

The basic intent of the model is to provide information needed to determine the minimum life-cycle cost (LCC) configuration of the installation's energy generation and consumption infrastructure. When determining the minimum LCC configuration of generation and end-use technologies, all interactive effects between energy systems are explicitly modeled. For example, when considering a lighting retrofit, the model evaluates the change in energy consumption in all building energy systems rather than just the change in the lighting energy. The value or cost of these interactive effects varies by building type (level of internal gain), building size (portion of heating, ventilation and air conditioning loads attributable to internal gains versus envelope gains/losses), climate (whether a particular building is cooling- or heating-dominated), occupancy schedule and a number of other factors. Thus, there is no simple solution and detailed modeling, as is done in FEDS, is the best way to provide a credible estimate of the impact (PNNL, 2008).

The inferences about the building characteristics in FEDS are mostly obtained from the following sources:

- Non-residential Building Energy Consumption Survey (NBECS) and Residential Energy Consumption Survey (RECS) building characteristics data
- End-use Load and Conservation Assessment Program (ELCAP) commercial and residential end-use load and building characteristics data
- American Society for Heating Refrigeration and Air-conditioning Engineers (ASHRAE) standard design and construction practices.

The FEDS analysis process briefly consists of the followings steps:

1. Determine the building set breakdown.

   For large installations, with hundreds or thousands of buildings, FEDS is designed to model groups of buildings that can be categorized together into sets.

2. Complete an initial minimum set screening.

The objective of the FEDS minimum set input is to provide a top-level screening as a preliminary indication of what actions should be initiated; further analysis is required before a project is designed and implemented.

3. Gather additional data about the buildings and central energy plants on the installation.

   Results from the minimum set screening can be used to direct resources for additional data-gathering. The building types, end-uses and fuels with the largest potential savings (according to the screening) are the building types, end-uses and fuels that should be given the most time and money for additional data-gathering.

4. Select maximum detail display for selected building sets and modify inferred data.

   The objective of FEDS maximum detail is to allow a knowledgeable user to override the default building and energy-using/generating equipment parameters that were inferred at minimum set. Unlike other models that require detailed inputs, this approach allows but does not require the user to enter any site-specific information that is not readily available.

5. Set optimization parameters.

   The optimization parameters should be set to best suit one’s needs. The following optimization parameter options should be reviewed:

   - Select funding source
   - Set financial screening options
   - Exclude building sets that should not be considered for retrofits

- Restrict retrofit technologies or end uses that one does not want to evaluate
- Alter cost data
- Review emission factors
- Choose whether the output spreadsheet lists the optimal retrofits only or the top 3 retrofits
- Select any 'replacement required' flags for those technologies that must be replaced

6. Run model on final maximum detail input data

   Once the data has been checked and modified by the user and inferred by FEDS, it is recommended that all building sets be excluded from optimization and then run FEDS to determine baseline consumption estimations. This allows the user to quickly get baseline information that one can check against real data and resolve any large discrepancies before doing a full run of the model. Once large discrepancies have been resolved, building set exclusions must be removed and the user should run the model.

Chapter 4

METHODOLOGY

4.1 Overview

This study aims at analyzing the various benchmarking tools by comparing the Energy Use Intensities (EUIs) and corresponding ratings given to the 90.1 Prototype Building Models for large office buildings for the ASHRAE 90.1 – 2004, ASHRAE 90.1 – 2007 and ASHRAE 90.1 – 2010 standards, Commercial Reference Buildings and several case-study buildings of different typologies from the Energize Phoenix program.

4.1.1 Commercial Reference Buildings

The U.S. Department of Energy (DOE), in conjunction with three of its national laboratories, the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), and Lawrence Berkeley National Laboratory (LBNL) has developed commercial reference buildings, formerly known as commercial building benchmark models. These reference buildings play a critical role in the program's energy modeling software research by providing complete descriptions for whole building energy analysis using EnergyPlus simulation software.

There are 16 building types that represent approximately 70% of the commercial buildings in the U.S., according to the report published by the National Renewable Energy Laboratory titled *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock* (Deru, et al., 2011).

There are three versions of the reference building models for each building type: new construction, post-1980 construction and pre-1980 construction. All have the same building form and area and the same operation schedules. The differences are reflected in the insulation values, lighting levels and HVAC equipment types and efficiencies. The new construction models comply with the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 (ASHRAE 2004a), the post-1980 models meet the minimum requirements of Standard 90.1-1989 (ASHRAE 1989) and the pre-1980 models are built to a set of requirements developed from previous standards and other studies of construction practices.

This study uses the Commercial Reference Building – Large Office – Post-1980 construction model for EUI comparisons. This model has been described in detail in Appendix B.

4.1.2 90.1 Prototype Building Models

The 90.1 Prototype Building Models were developed by Pacific Northwest National Laboratory (PNNL) in support of DOE's Building Energy Codes Program (BECP). PNNL developed the prototype models to quantify the energy impacts based on the newly- developed addenda and ultimately to indicate progress toward the 30% energy savings goal in 90.1-2010 over 90.1-2004 (US DOE, 2011). These prototype buildings were derived from DOE's Commercial Reference Building Models. As Standard 90.1 evolved, PNNL also made substantial modifications to the Commercial Reference Building Models with extensive inputs from 90.1 committee members and other building industry experts.

This study utilizes the 90.1 Prototype Building Models for large office buildings for all the three ASHRAE Standards – 90.1-2004, 90.1-2007 and 90.1-2010. The building details common to all the three models are described in Appendix C.

4.1.3 Case-study Building

The facility is a 27 story multi-tenant commercial office building in Phoenix, Arizona built in the year 1980 with an area of 401,260 ft^2. The building has an average occupancy of 933 occupants.

Existing Conditions

The existing HVAC system of the building consisted of a Central Plant in the basement with the cooling towers located on the roof. Chilled water was produced using two 30-plus year old 900 Ton Trane Centrifugal Chillers with an original design rating of 0.754 kW/Ton. These chillers were over-sized for the cooling loads of the building and so these chillers were operated under low loading conditions for much of the year which resulted in higher energy consumption overall.

There are two cooling towers located on the roof. Each tower has 700 tons of cooling capacity. All chilled water system components are currently controlled by an Alerton BACNET Energy Management System (EMS).

On the air side of the HVAC system, the primary air is provided by four large air handler units. All supply fans were driven by 125 HP fans with variable frequency drive (VFD). These fans were also recently upgraded with VFD's in February 2009. Two of these air handlers are located in the basement and the other two are located on the 27th floor. Air handlers are ducted in the four corners of the building and air is distributed by fan powered variable air volume (FPVAV) boxes at the perimeter and variable air volume (VAV) boxes in the interior. There are an estimated 30 FPVAV & VAV terminal units per floor. There are also several DX units & smaller air handler units throughout the facility serving specific areas. Air side controls consist of Alerton BACNET EMS on the four large air handler units and smaller area specific units. The remaining air distribution units are not control by the EMS; they are controlled by a pneumatic system from the original installation. The pneumatic system had two large air compressors that were extremely inefficient and require continued maintenance to overcome air losses throughout the building.

Lighting was also upgraded from T12 U-tube light to high efficiency T8 U-tubes in January 2009. Though the lighting system is operated efficiently, lights are not on motion sensors or any other lighting controls. This retrofit was not part of the Energize Phoenix project and so the building post-lighting retrofit is taken as the baseline for the energy savings determination.

4.2 Benchmarking

The 90.1 Prototype Models which conform to ASHRAE Standards 90.1 – 2004, 90.1 – 2007 and 90.1 – 2010 for Large Office building type alongwith the Commercial Reference Building model for Large Office building type are benchmarked using the ORNL Spreadsheet and Portfolio Manager.

The basic information required by both these tools includes:

- Type of building
- Location of the building

- Year of construction
- Gross floor area
- Weekly operating hours
- No. of occupants
- No. of computers
- Monthly and Annual energy consumption data for different fuels

The energy use intensities for these models and the ratings given on the basis of comparison with the national average energy use intensities by these two tools are analytically compared.

As a second part of the benchmarking comparative analysis, the ORNL Spreadsheet and Portfolio Manager are used to benchmark different existing commercial buildings from the Energize Phoenix program which are used as case-studies. These existing commercial buildings belong to different typologies and have a varied range of floor areas. The utility data of these buildings is used for the energy consumption data required by the benchmarking tools.

4.3 Retrocommissioning/Auditing

The 90.1 Prototype Models which conform to ASHRAE Standards 90.1 – 2004, 90.1 – 2007 and 90.1 – 2010 for Large Office building type alongwith the Commercial Reference Building model for Large Office building type are modeled in FEDS using the maximum detail mode with the help of the information available from the EnergyPlus models for these prototypes. The calculated energy consumption values, energy use intensities and the recommended retrofits are further analyzed. The energy savings calculated by FEDS from the recommended retrofits are compared to the energy savings calculated by modeling the same retrofits in the existing EnergyPlus models.

As a second part of retrocommissioning/auditing analysis, the existing commercial buildings from the Energize Phoenix program used as case-studies for benchmarking are modeled in FEDS using the minimum input mode with the help of the information available from the commercial surveys collected from the participants in the Energize Phoenix program. One large office case-study building is modeled using the maximum detail mode with the help of information available from its e-Quest model provided by the auditor/contractor. The FEDS calculated energy consumption data for all these buildings is compared to their pre-retrofit utility data. The energy use intensities for these buildings calculated by FEDS are compared to those computed by the benchmarking tools. The retrofits recommended by FEDS are analyzed and compared to the actual retrofits being carried out.

Chapter 5

ANALYSIS

As described in the methodology, the study consisted of two distinct phases – benchmarking and retrocommissioning/auditing. The benchmarking study was undertaken using the benchmarking tools Portfolio Manager and the ORNL Spreadsheet so as to compare the Energy Use Intensities for the different prototype models as well as for case-study buildings from the Energize Phoenix Program. The retrocommissioning/auditing study was undertaken by modeling the prototypes and the case-study buildings in FEDS to analyze the recommended retrofits. The Energy Use Intensity values obtained from FEDS for the prototype models and the case-study buildings have also been used for EUI comparison in the benchmarking analyses.

5.1 Benchmarking Prototype Models

This part of the benchmarking analyses focuses on benchmarking the various prototype models described in the methodology using Portfolio Manager and the ORNL Spreadsheet. The EUI comparative results for the benchmarking have been classified on the basis of fuel types and have also been computed for the total energy consumption for all these models.

Portfolio Manager gives an output of the Energy Use Intensity for the total energy consumption and does not distinguish the results on the basis of fuel types. The ORNL Spreadsheets calculate the Energy Use Intensities using two distinct spreadsheets on the basis of fuel types: Electric and Non-electric. FEDS computes the Energy Use Intensities for different fuel types as well as for the total energy consumption – a combined value for all the different types of fuels.

Table 11: Site Electric Energy Use Intensity (EUI) Comparison for Prototype models

SITE ELECTRIC ENERGY USE INTENSITY				
Large Office Building - Climate Zone 2B	**ORNL**			**FEDS**
	EUI (kWh/ft²)	**Typical Building EUI (kWh/ft²)**	**Rating**	**EUI (kWh/ft²)**
Prototype 90.1 2004	12.6	43.7	95	12.74
Prototype 90.1 2007	12.0	43.7	95	11.3
Prototype 90.1 2010	9.5	43.7	95	10.8
Commercial Reference Building	17.2	43.7	95	16.3

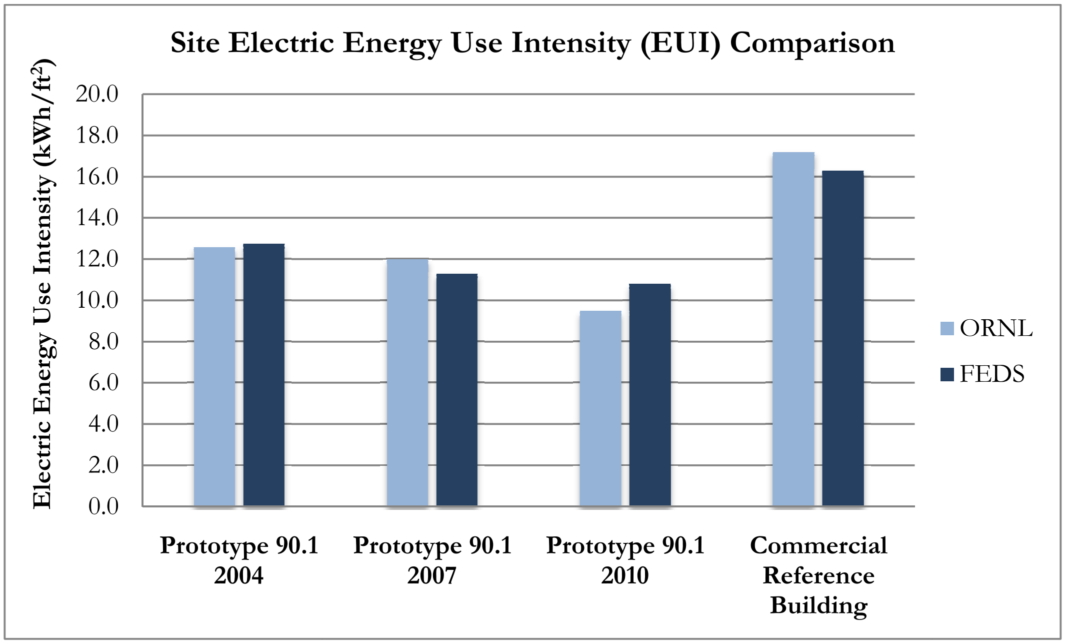


Figure 6: Site Electric Energy Use Intensity (EUI) Comparison for Prototype models

This comparative study establishes that the values of EUIs for electricity use predicted by the ORNL Spreadsheet and FEDS are very similar.

Table 12: Site Non-electric Energy Use Intensity (EUI) Comparison for Prototype models

SITE NON - ELECTRIC ENERGY USE INTENSITY				
Large Office Building - Climate Zone 2B	**ORNL**			**FEDS**
	EUI (kBtu/ft²)	**Typical Building EUI (kBtu/ft²)**	**Rating**	**EUI (kBtu/ft²)**
Prototype 90.1 2004	3.2	34.7	97	5.5
Prototype 90.1 2007	2.0	34.7	97	3.1
Prototype 90.1 2010	0.5	34.7	97	1.6
Commercial Reference Building	3.3	34.7	90	5.1

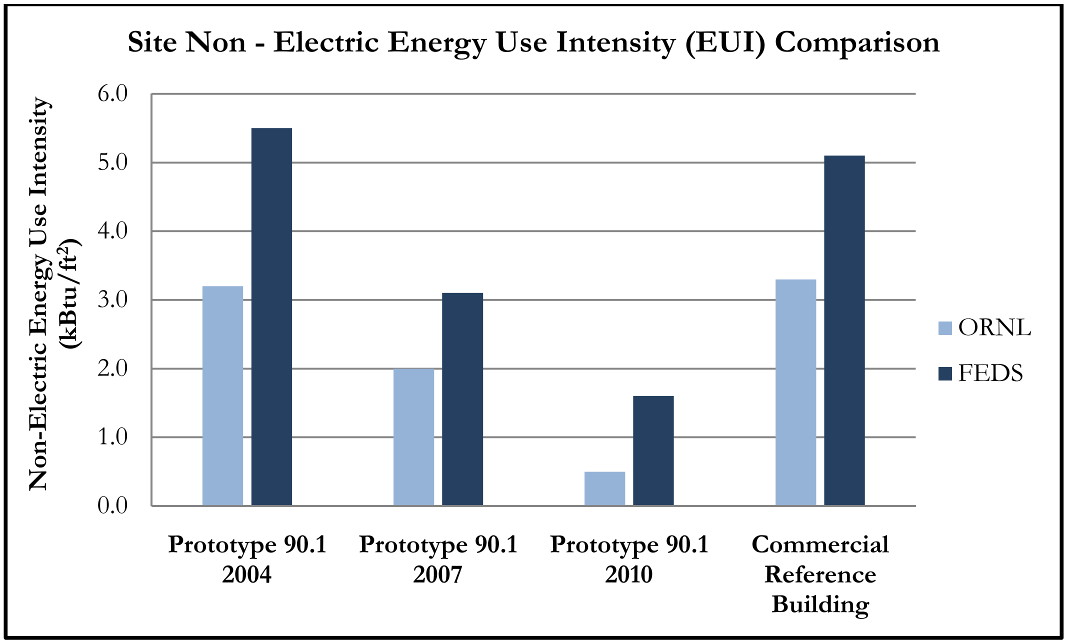


Figure 7: Site Non-electric Energy Use Intensity (EUI) Comparison for Prototype models

This comparative analysis established that the values for EUIs for non-electric (natural gas) predicted by the ORNL spreadsheet and FEDS are not quite distinct from each other.

Table 13: Site Total Energy Use Intensity (EUI) Comparison for Prototype models

SITE TOTAL ENERGY USE INTENSITY						
Large Office Building - Climate Zone 2B	Portfolio Manager			ORNL		FEDS
	Total EUI (kBtu/ft^2)	National Median EUI (kBtu/ft^2)	Rating	Total Calculated EUI (kBtu/ft^2)	Total Calculated Typical Building EUI (kBtu/ft^2)	Total EUI (kBtu/ft^2)
Prototype 90.1 2004	46.1	90.5	92	46.2	183.80	50.2
Prototype 90.1 2007	43.0	89.0	94	43.0	183.80	41.9
Prototype 90.1 2010	33.0	87.0	98	32.9	183.80	36.7
Commercial Reference Building	62.0	91.1	80	61.9	183.80	62.1

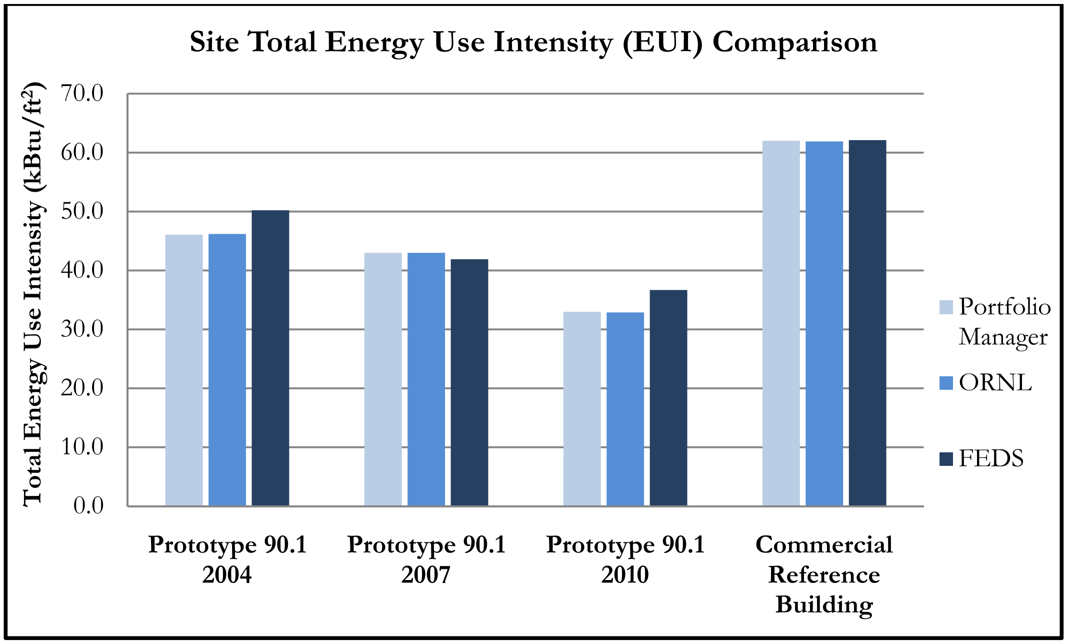


Figure 8: Site Total Energy Use Intensity (EUI) Comparison for Prototype models

The site total EUIs for all the prototype models are compared with the help of Portfolio Manager, ORNL Spreadsheet and FEDS. The results of this analysis proved that the values of site total EUIs predicted by all these tools are very similar. It was also observed that in case of the ORNL Spreadsheet and the FEDS tool, the total EUI was the aggregate of the electric and non-electric EUIs (after appropriate conversions).

Thus, it can be concluded that FEDS predicts the electric EUI accurately but is not very accurate at predicting the natural gas EUI. But since natural gas consumption is a very small part of the total energy consumption for the large office typology for Phoenix (Climate zone: 2B), the total EUI predicted by FEDS for all these prototype models is accurate and comparable to that predicted by Portfolio Manager and the ORNL Spreadsheet. However, it should be noted that, using FEDS, for other building typologies where the natural gas consumption is higher or for other climate zones which are heating dominated and use natural gas based heating systems, might not yield accurate results.

The 90.1 Prototype models and the Commercial Reference Building model were further analyzed using the results from Portfolio Manager, comparing their energy use intensities to a national average thereby computing their ratings.

Table 14: Portfolio Manager - EUIs and Ratings Comparison for Prototype models

PORTFOLIO MANAGER - EUIs AND RATINGS			
Large Office Building - Climate Zone 2B	**Total EUI (kBtu/ft^2)**	**National Median EUI (kBtu/ft^2)**	**Rating**
Prototype 90.1 2004	46.1	90.5	92
Prototype 90.1 2007	43.0	89.0	94
Prototype 90.1 2010	33.0	87.0	98
Commercial Reference Building	62.0	91.1	80

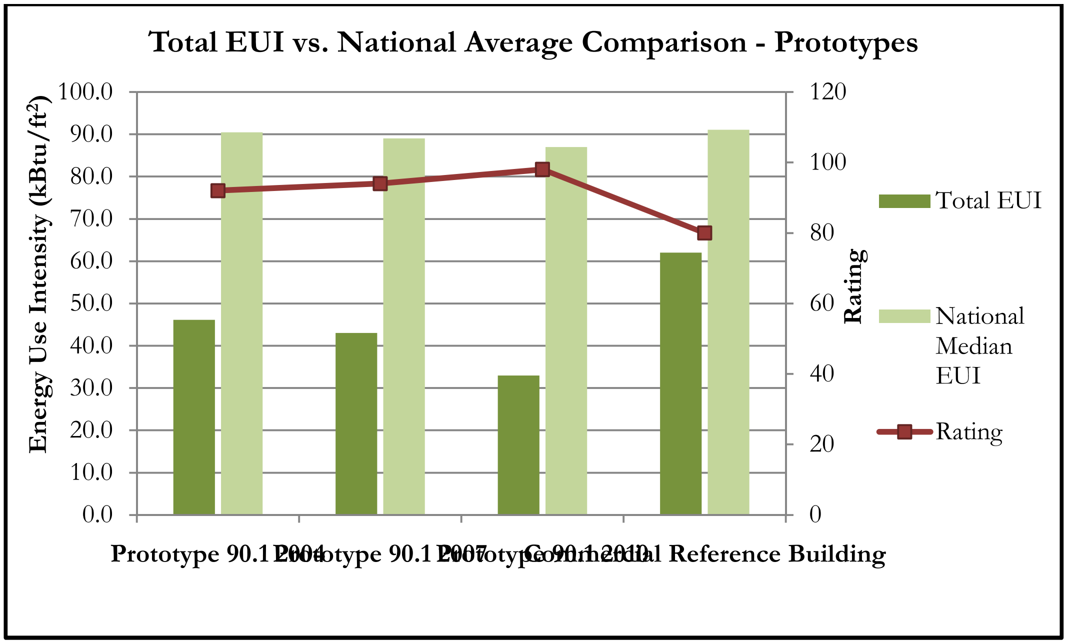


Figure 9: Portfolio Manager - EUIs and Ratings Comparison for Prototype Models

The 90.1 Prototype models were developed to help the ASHRAE committee formulate the ASHRAE 90.1 – 2010 standards such that they could achieve 30% energy savings needed to be achieved over the ASHRAE 90.1 – 2004 standards. Table 14 explicitly depicts the decrease in the total EUI of 90.1 – 2007 Prototype to be approximately 7% over 90.1 – 2004 Prototype and that of 90.1 – 2010 Prototype to be approximately 30% over 90.1 – 2004 Prototype. This decrease in the total EUI translates to an increasing rating given by Portfolio Manager by comparing the calculated EUI to the national median EUI as described in the methodology.

5.2 Benchmarking Case-Study Building

The case-study building used for this study is a large office building in downtown Phoenix from the Energize Phoenix program. This building was analyzed for its electric, non-electric and total energy use intensity both during pre and post retrofit periods using Portfolio Manager, ORNL Spreadsheet and FEDS.

Table 15: Site Electric Energy Use Intensity (EUI) Comparison for Case-study Building

SITE ELECTRIC ENERGY USE INTENSITY				
Large Office Building - Climate Zone 2B	**ORNL**			**FEDS**
	EUI (kWh/ft²)	**Typical Building EUI (kWh/ft²)**	**Rating**	**EUI (kWh/ft²)**
Case Study Bldg - Pre-retrofit	32.9	25.1	30	29.9
Case Study Bldg - Post-retrofit	32.0	25.1	30	27.1

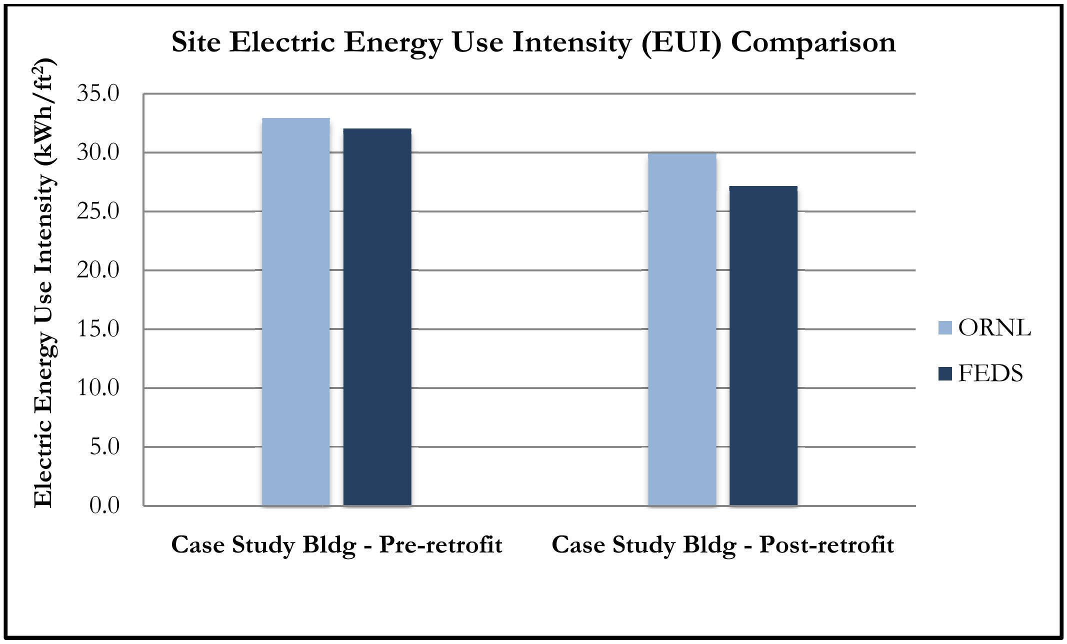


Figure 10: Site Electric Energy Use Intensity (EUI) Comparison for Case-study Building

As described in Table 15, when the site-electric energy consumption data was input in the ORNL Spreadsheet to benchmark the energy use of the case-study building, the calculated Site Electric EUI for the case-study building before retrofitting was found to be 32.9 kWh/ft^2 as compared to the typical building EUI of 25.1 kWh/ft^2. This gave the building a rating of 30 for its electric energy use.

When the building was modeled in FEDS using the information available from the e-Quest model procured from the contractors, the Site Electric EUI calculated by FEDS was 29.9 kWh/ft^2.

The post-retrofit utility data for the case-study building is available only for 6 months as the retrofit was completed only in early March 2011. When the post-retrofit electricity consumption data for 6 months alongwith 6 months worth of pre-retrofit electricity consumption data was input in the ORNL Spreadsheet, the Site Electric EUI was computed to be 32.0 kWh/ ft^2 as compared to the typical building EUI of 25.1 kWh/ft^2, thereby giving it a rating of 30 for its electric energy use.

When the case-study building was modeled in FEDS, certain retrofit measures were suggested by the tool. The post-retrofit site electric EUI calculated by FEDS is based on the electricity consumption of the building after the recommended retrofit measures have been implemented. The FEDS calculated post-retrofit site electric EUI is 28.9 kWh/ft^2.

The case-study building was then benchmarked for its non-electric (natural gas) consumption using the ORNL Spreadsheet and FEDS. The natural gas consumption data for the case-study building was obtained from the e-Quest model, though it was found to be a not well calibrated model, as the utility data for natural gas consumption was not available.

Table 16: Site Non-Electric Energy Use Intensity (EUI) Comparison for Case-study Building

SITE NON - ELECTRIC ENERGY USE INTENSITY COMPARISON				
Large Office Building - Climate Zone 2B	**ORNL**			**FEDS**
	EUI (kBtu/ft²)	**Typical Building EUI (kBtu/ft²)**	**Rating**	**EUI (kBtu/ft²)**
Case Study Bldg - Pre-retrofit	13.1	34.7	65	10.8
Case Study Bldg - Post-retrofit	10.5	34.7	70	9.8

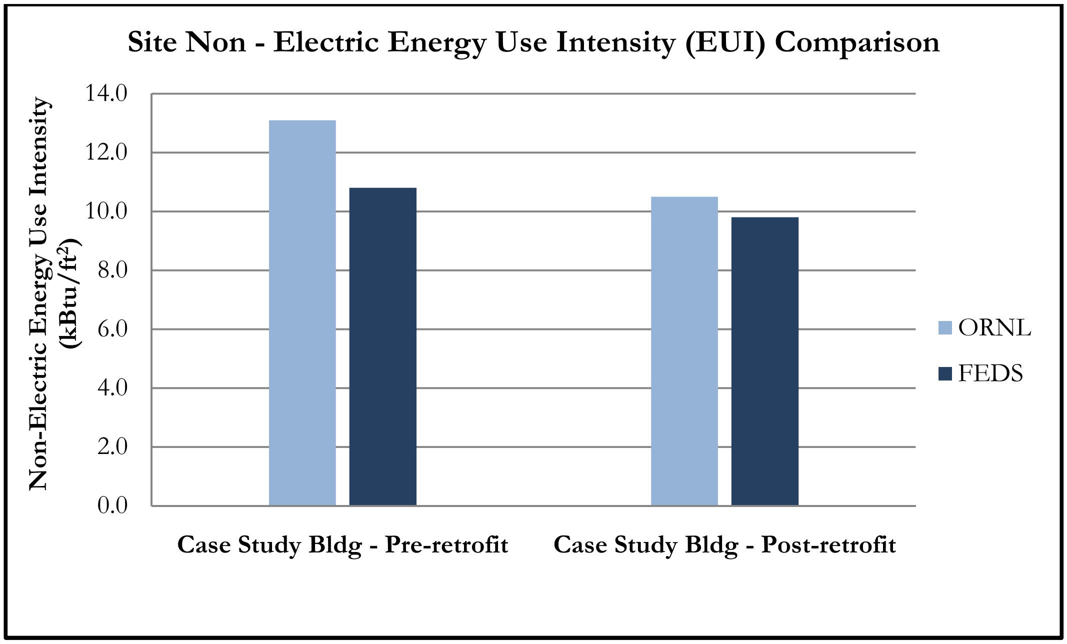


Figure 11: Site Non-Electric Energy Use Intensity (EUI) Comparison for Case-study Building

According to the ORNL Spreadsheet, the site non-electric EUI for the case-study building pre-retrofit was calculated as 13.1 kBtu/ft^2 as compared to the typical building non-electric EUI of 34.7 kBtu/ft^2, thus giving it a rating of 65. The post-retrofit natural gas consumption data was obtained from the e-Quest model. The calculated post-retrofit site non-electric EUI for the case-study building was 10.5 kBtu/ft^2, thereby giving it a rating of 70.

The post-retrofit natural gas consumption data was calculated by FEDS considering that the recommended retrofits have been implemented. The post-retrofit site natural gas EUI calculated by FEDS is 9.8 kBtu/ft^2.

A comparative analysis of the total site energy EUIs for the Case-study Building was done using the benchmarking results from Portfolio Manager, ORNL Spreadsheet and FEDS.

Table 17: Site Total Energy Use Intensity (EUI) Comparison for Case-study Building

SITE TOTAL ENERGY USE INTENSITY						
Large Office Building - Climate Zone 2B	**Portfolio Manager**			**ORNL**		**FEDS**
	Total EUI (kBtu/ft^2)	**National Median EUI (kBtu/ft^2)**	**Rating**	**Total Calculated EUI (kBtu/ft^2)**	**Total Calculated Typical Building EUI (kBtu/ft^2)**	**Total EUI (kBtu/ft^2)**
Case Study Bldg - Pre-retrofit	126.2	107	34	125.4	120.34	106.1
Case Study Bldg - Post-retrofit	119.6	106.3	39	119.5	120.34	96.2

The total site EUI as calculated by Portfolio Manager for the case-study building using the utility data before the retrofits were implemented is 126.2 kBtu/ft^2 as compared to the national median of 107 kBtu/ft^2, thereby giving it a rating of 34. The ORNL Spreadsheet does not give a direct value for the total EUI. This has been calculated using the values for the electric and non-electric EUI. This value comes out to be 125.4 kBtu/ft^2 whereas the typical building total calculated EUI comes out to be 120.34 kBtu/ft^2. The total EUI as calculated by FEDS is 124.9 kBtu/ft^2 before the retrofit implementation. After implementing the retrofits suggested by FEDS, the total EUI comes out to be 102.4 kBtu/ft^2.

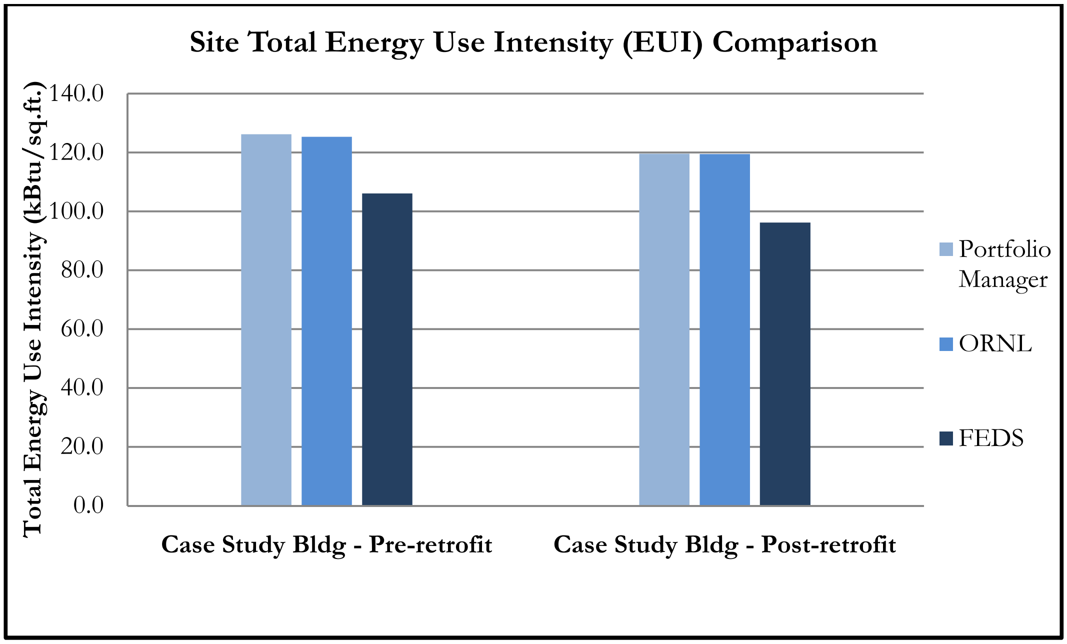


Figure 12: Site Total Energy Use Intensity (EUI) Comparison for Case-study Building

Thus, when the details of the case-study building were input in Portfolio Manager and the ORNL Spreadsheet, both the tools calculated the pre-retrofit site EUI for the building and compared it to a national median or average.

Portfolio Manager gave the case-study building a rating of 34 for the total EUI as compared to the national average. For any building to classify for the Energy Star (for buildings), it should get a minimum rating of 75. To achieve a rating of 75, Portfolio Manager estimates approximately 37% reduction in the total energy use from the baseline consumption data. Thus, benchmarking a building for its total energy use gives the building owner/contractor an idea of where the building stands with respect to its peers in terms of its energy use. It proves to be a quick and easy way to encourage the building owners to audit their energy use, retro-commission the building if needed to get a higher rating and be eligible for an Energy Star.

The case-study building gets an average rating of approximately 35 using the ORNL Spreadsheets for electric and non-electric EUI. According to Table 4, the ORNL Spreadsheet estimates an energy savings potential of 35 – 50 % and recommends a walk-through energy assessment for the building.

5.3 Retrocommissioning/Auditing Prototype Models

The 90.1 Prototype models and the Commercial Reference Building model for the large office building typology for Phoenix (climate zone 2B) were modeled in the retrocommissioning/auditing software – FEDS.

5.3.1 Estimated Energy Consumption

The 90.1 Prototype models, Commercial Reference Building model and the Case-study Building were modeled in FEDS, primarily, to validate the accuracy of the energy consumption calculated by FEDS for all these prototypes by comparing it to that available from the Energy Plus model results for these prototypes and from the electricity utility bill for the Case-study Building.

Table 18: Pre-retrofit Energy Consumption Comparison between FEDS and EnergyPlus/Utility Bill

PRE-RETROFIT ENERGY CONSUMPTION						
Large Office Building - Climate Zone 2B	**Electricity (kWh)**		**Natural Gas (kBtu)**		**Total Energy (kBtu)**	
	FEDS	**Energy Plus/ Utility Bills**	**FEDS**	**Energy Plus/ Utility Bills**	**FEDS**	**Energy Plus/ Utility Bills**
Prototype 90.1 2004	6,355,686	6,267,581	2,724,700	1,615,365	25,033,000	23,001,247
Prototype 90.1 2007	5,642,158	5,989,908	1,528,200	974,849	20,899,000	21,413,264
Prototype 90.1 2010	5,386,424	4,746,511	1,094,400	534,569	20,178,000	16,730,337
Commercial Reference Building	8,138,068	8,575,314	2,197,400	1,628,786	30,973,000	30,891,455
Case Study Building	12,024,150	13,218,600	1,518,000	NA	42,554,000	NA

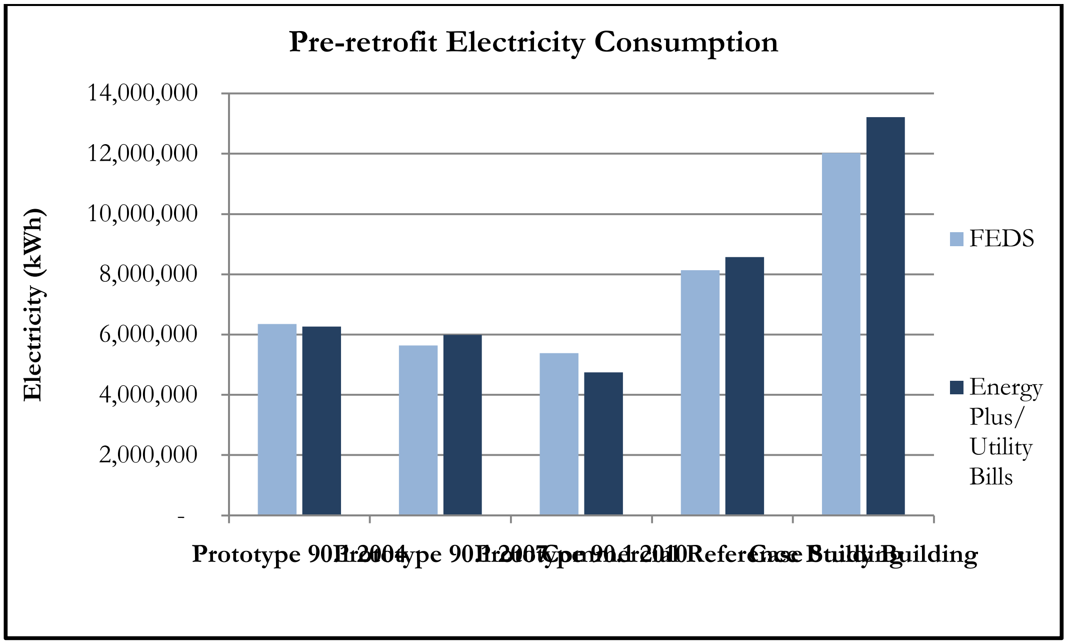


Figure 13: Pre-retrofit Electricity Consumption Comparison between FEDS and EnergyPlus/Utility Bill

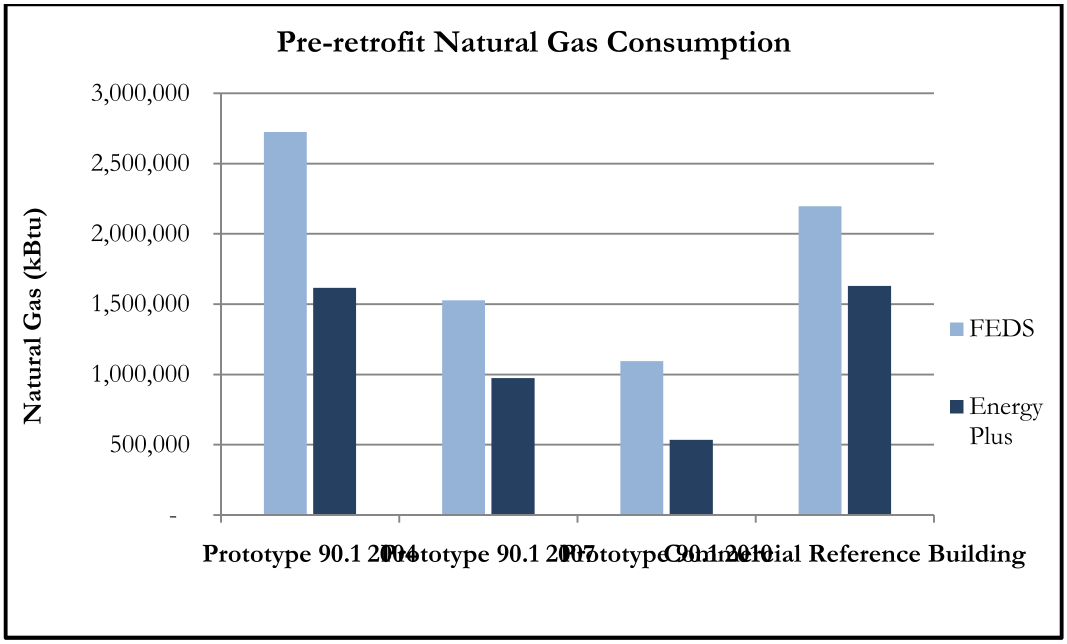


Figure 14: Pre-retrofit Natural Gas Consumption Comparison between FEDS and EnergyPlus

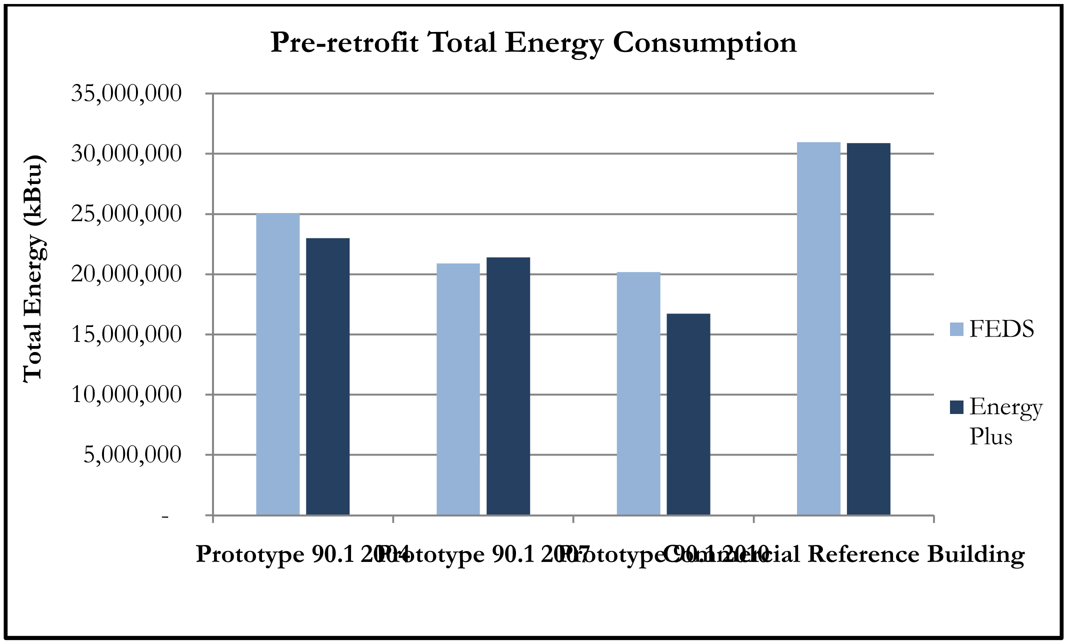


Figure 15: Pre-retrofit Total Energy Consumption Comparison between FEDS and EnergyPlus

From Table 18 and Figure 13, Figure 14 and Figure 15, it is evident that FEDS predicts the electricity consumption very well when compared to EnergyPlus results for the Prototype models as well as the actual electricity utility bill for the case-study building. However, it is not very good at predicting the natural gas consumption when compared to the EnergyPlus results for the Prototype models. The estimated value for the total energy consumption is nearly accurate when compared to the results from the EnergyPlus model for the different prototypes, as the component of natural gas usage in the total energy consumption is very low for a large office building in the climate of Phoenix.

5.3.2 Recommended Retrofits

The 90.1 Prototype models and the Commercial Reference Building model for large office were modeled in FEDS to discuss and analyze the retrofits suggested by FEDS over the Prototype models that confirmed to the ASHRAE 90.1 – 2004, 90.1 – 2007 and 90.1 – 2010 Standards.

The retrofits suggested by FEDS over the **90.1 – 2004 Prototype** model for Large Office building typology for Phoenix climate (Climate Zone: 2B) are as noted below:

A. Heating

Replace the existing natural gas conventional boiler with an efficiency of 79.3% to -

Rank	Efficiency
1	80%
2	81.5%
3	84%

B. Cooling

Replace the existing water-cooled centrifugal electric chiller with a COP of 6.1 to

Rank	COP
1	4.19
2	4.60
3	5.11

C. Lights

Replace the existing 4 foot 2x4 40 watt T12 lamps with one magnetic ballast and reflectors to

Rank	Retrofit
1	4 foot 2x4 32 watt T8 lamps with 2 electronic ballasts and reflectors
2	4 foot 2x4 32 watt T8 lamps with 1 electronic ballast and reflectors
3	4 foot 2x4 32 watt Standard T8 lamps with 1 electronic ballast and reflectors

D. Lights

Replace the existing LED – Exit signs with 2 Watts/fixture wattage to Electroluminescent Panel with

Rank	Retrofit
1	0.2 Watts/fixture
2	0.35 Watts/fixture

E. Hot Water

Replace the existing natural gas central boiler with an efficiency of 80% to a conventional gas boiler with

Rank	Retrofit
1	80% Combustion efficiency, wrap tank
2	80% Combustion efficiency
3	81.5 Combustion efficiency, wrap tank

F. Motors

Replace the existing cooling systems pump 20.0 hp open drip proof motor with an efficiency of 90% to an energy efficient 20.0 hp motor with

Rank	Efficiency
1	91%
2	93.6%

G. Motors

Replace the existing water tower systems pump 75.0 hp open drip proof motor with an efficiency of 87% to an energy efficient 75.0 hp motor with

Rank	Efficiency
1	94.1%
2	95%

H. Motors

Replace the existing cooling systems secondary pump 60.0 hp open drip proof motor with an efficiency of 90% to an energy efficient 60.0 hp motor with

Rank	Efficiency
1	93.6%
2	95.4%
3	94.5%

I. Motors

Replace the existing heating systems pump 40.0 hp open drip proof motor with an efficiency of 90% to an energy efficient 40.0 hp motor with

Rank	Efficiency
1	93.0%
2	94.5%

J. Window

Replace the existing metal frame single pane window with aluminum frame –

Rank	Retrofit
1	Double pane window
2	Double pane Low-e window
3	Double pane Argon/Low-e window

The retrofits suggested by FEDS over the **90.1 – 2007 Prototype** model for Large Office building typology for Phoenix climate (Climate Zone: 2B) are as noted below:

A. Heating

Replace the existing natural gas conventional boiler with an efficiency of 79.3% to -

Rank	Efficiency
1	80%
2	81.5%
3	84%

B. Cooling

Replace the existing water-cooled centrifugal electric chiller with a COP of 6.1 to

Rank	COP
1	4.16
2	4.57
3	5.06

C. Lights

Replace the existing 4 foot 2x4 40 watt T12 lamps with one energy efficient ballast to

Rank	Retrofit
1	4 foot 2x4 32 watt T8 lamps with 2 electronic ballasts

2	4 foot 2x4 32 watt Standard T8 lamps with 1 electronic ballast
3	4 foot 2x4 30 watt Standard T8 lamps with 1 electronic ballast

D. Lights

Replace the existing LED – Exit signs with 2 Watts/fixture wattage to Electroluminescent Panel with

Rank	Retrofit
1	0.2 Watts/fixture
2	0.35 Watts/fixture

E. Hot Water

Replace the existing natural gas central boiler with an efficiency of 80% to a conventional gas boiler with

Rank	Retrofit
1	80% Combustion efficiency, wrap tank
2	80% Combustion efficiency
3	81.5% Combustion efficiency, wrap tank

F. Motors

Replace the existing cooling systems pump 20.0 hp open drip proof motor with an efficiency of 90% to an energy efficient 20.0 hp motor with

Rank	Efficiency
1	91%
2	93.6%

G. Motors

Replace the existing water tower systems pump 75.0 hp open drip proof motor with an efficiency of 87% to an energy efficient 75.0 hp motor with

Rank	Efficiency
1	94.1%
2	95%

H. Motors

Replace the existing cooling systems secondary pump 60.0 hp open drip proof motor with an efficiency of 90% to an energy efficient 60.0 hp motor with

Rank	Efficiency
1	93.6%
2	95.4%
3	94.5%

I. Motors

Replace the existing heating systems pump 40.0 hp open drip proof motor with an efficiency of 90% to an energy efficient 40.0 hp motor with

Rank	Efficiency
1	93.0%
2	94.5%

J. Window

Replace the existing metal frame single pane window with aluminum frame –

Rank	Retrofit
1	Double pane window
2	Double pane Low-e window
3	Double pane Argon/Low-e window

The retrofits suggested by FEDS over the **90.1 – 2010 Prototype** model for Large Office building typology for Phoenix climate (Climate Zone: 2B) are as noted below:

A. Heating

Replace the existing natural gas conventional boiler with an efficiency of 81.3% to -

Rank	Efficiency
1	80%
2	81.5%
3	84%

B. Cooling

Replace the existing water-cooled centrifugal electric chiller with a COP of 5.86 to

Rank	COP
1	4.16
2	4.57
3	5.06

C. Lights

Replace the existing 4 foot 2x4 32 watt T8 lamps with one electronic ballast to

Rank	Retrofit
1	4 foot 2x4 32 watt Standard T8 lamps with 2 electronic ballasts (Component replacement)
2	4 foot 2x4 30 watt Standard T8 lamps with 1 electronic ballast
3	4 foot 2x4 32 watt Standard T8 lamps with 1 electronic ballast

D. Lights

Replace the existing LED – Exit signs with 2 Watts/fixture wattage to Electroluminescent Panel with

Rank	Retrofit
1	0.2 Watts/fixture
2	0.35 Watts/fixture
3	Self-luminous – 0 Watts/fixture

E. Hot Water

Replace the existing natural gas central boiler with an efficiency of 80% to a conventional gas boiler with

Rank	Retrofit
1	80% Combustion efficiency, wrap tank
2	80% Combustion efficiency
3	81.5% Combustion efficiency, wrap tank

F. Motors

Replace the existing cooling systems pump 15.0 hp motor with an efficiency of 90% to an energy efficient 15.0 hp motor with

Rank	Efficiency
1	92.4%
2	93.0%

G. Motors

Replace the existing water tower systems pump 60.0 hp motor with an efficiency of 87% to an energy efficient 60.0 hp motor with

Rank	Efficiency
1	93.6%
2	95.4%
3	94.5%

H. Motors

Replace the existing cooling systems secondary pump 40.0 hp motor with an efficiency of 90% to an energy efficient 40.0 hp motor with

Rank	Efficiency
1	93.0%
2	95.4%

I. Motors

Replace the existing heating systems pump 40.0 hp motor with an efficiency of 90% to an energy efficient 40.0 hp motor with

Rank	Efficiency
1	93.0%
2	94.5%

J. Window

Replace the existing metal frame single pane window with aluminum frame –

Rank	Retrofit
1	Double pane window
2	Double pane Low-e window
3	Double pane Argon/Low-e window

5.3.3 Estimated Energy Savings

The energy savings estimated by FEDS when the suggested retrofits are implemented have been evaluated by modeling the same retrofits in the existing EnergyPlus model for the 90.1 Prototype for ASHRAE 90.1 – 2007 Standards.

Table 19: Electricity Consumption and Savings Comparison between FEDS and EnergyPlus for Prototype 90.1 - 2007

ELECTRICITY CONSUMPTION and SAVINGS (kWh)				
	Pre-retrofit Electricity Consumption		Post-retrofit Electricity Savings	
	FEDS	Energy Plus	FEDS	Energy Plus
Prototype 90.1 2007	5,642,158	5,989,908	1,126,793	1,131,758

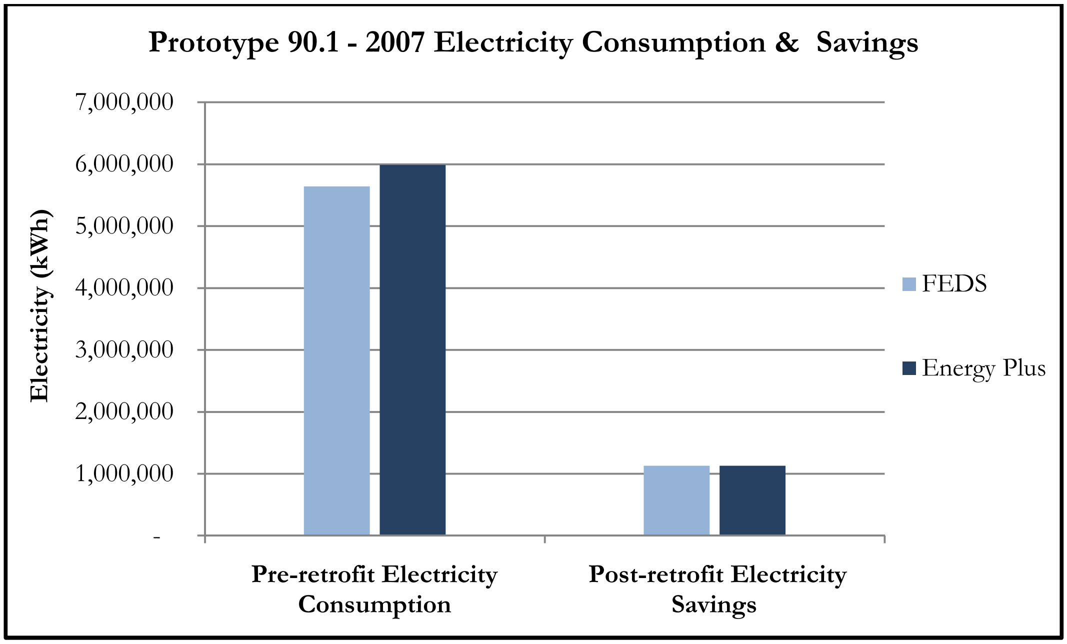


Figure 16: Electricity Consumption and Savings Comparison between FEDS and EnergyPlus for Prototype 90.1 – 2007

Table 19 and Figure 16 depict that the pre-retrofit electricity consumption calculated by FEDS is very accurate. When the retrofits recommended by FEDS over the Prototype 90.1-2007 were modeled in EnergyPlus, the electricity energy savings estimated by EnergyPlus are very accurate as compared to those estimated by FEDS.

Table 20: Natural Gas Consumption and Savings Comparison between FEDS and EnergyPlus for Prototype 90.1 - 2007

NATURAL GAS CONSUMPTION and SAVINGS (kBtu)				
	Pre-retrofit Natural Gas Consumption		Post-retrofit Natural Gas Savings	
	FEDS	Energy Plus	FEDS	Energy Plus
Prototype 90.1 2007	1,528,200	974,849	140,200	191,478

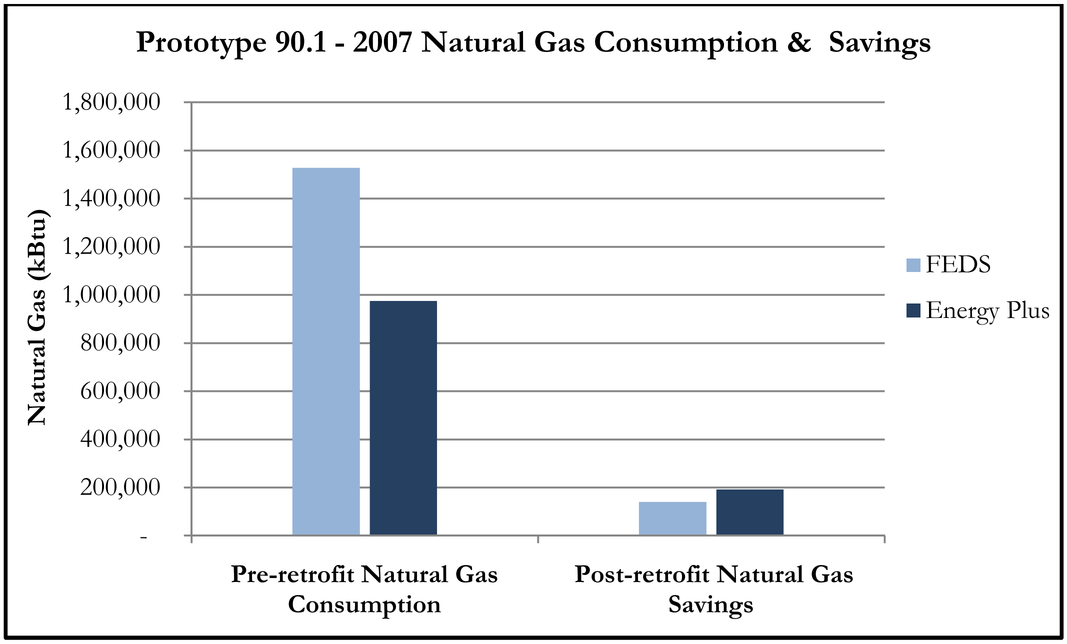


Figure 17: Natural Gas Consumption and Savings Comparison between FEDS and EnergyPlus for Prototype 90.1 - 2007

However, Table 20 and Figure 17 depict that the pre-retrofit natural gas consumption calculated by FEDS is not accurate when compared to that estimated by EnergyPlus. When the retrofits recommended by FEDS over the Prototype 90.1-2007 were modeled in EnergyPlus, the natural gas energy savings estimated by EnergyPlus are higher than those estimated by FEDS.

Table 21: Total Energy Consumption and Savings Comparison between FEDS and EnergyPlus for Prototype 90.1-2007

TOTAL ENERGY CONSUMPTION and SAVINGS (kBtu)				
	Pre-retrofit Total Energy Consumption		Post-retrofit Total Energy Savings	
	FEDS	Energy Plus	FEDS	Energy Plus
Prototype 90.1 2007	20,899,000	21,413,264	3,000,000	3,670,242

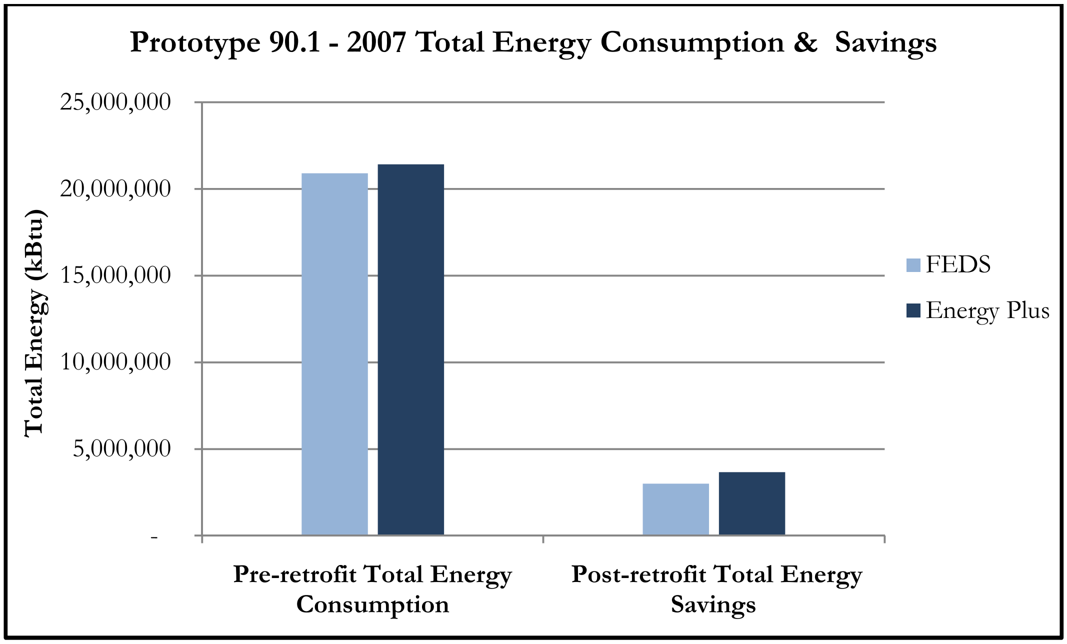


Figure 18: Total Energy Consumption and Savings Comparison between FEDS and EnergyPlus for Prototype 90.1 – 2007

Table 21 and Figure 18 depict that the pre-retrofit total energy consumption calculated by FEDS is accurate when compared to that estimated by EnergyPlus. When the retrofits recommended by FEDS over the Prototype 90.1-2007 were modeled in EnergyPlus, the total energy savings estimated by EnergyPlus are higher than those estimated by FEDS.

5.4 Retrocommissioning/Auditing Case-study Building

The case-study building (large office) in Phoenix from the Energize Phoenix program was modeled in FEDS using detailed information available from the e-Quest model procured from the contractors. The retrofit suggestions and the energy savings estimated by FEDS are compared to the actual retrofits being implemented and the energy savings estimated using e-Quest.

5.4.1 Estimated Energy Consumption

The case-study building was modeled in e-Quest by the contractors and modeled in FEDS as a part of this study. The pre-retrofit electricity consumption data for the building is available from the utility. This electricity consumption data from the utility is compared to that estimated by e-Quest and FEDS.

Table 22: Pre-retrofit Electricity Consumption Comparison between e-Quest, Utility Bills and FEDS

PRE-RETROFIT ELECTRICITY CONSUMPTION			
Large Office Building - Climate Zone 2B	**Electricity (kWh)**		
	e-Quest	**Utility Bills**	**FEDS**
Case Study Building	4,996,000	13,218,600	12,024,150

It is observed from Table 22 and Figure 19 that FEDS is accurate in simulating the pre-retrofit electricity consumption of the building when compared to the actual utility bills available for the building before the retrofits were implemented. The e-Quest model does not seem to be well calibrated and hence the estimated annual electricity consumption from e-Quest is very low as compared to the actual utility bills.

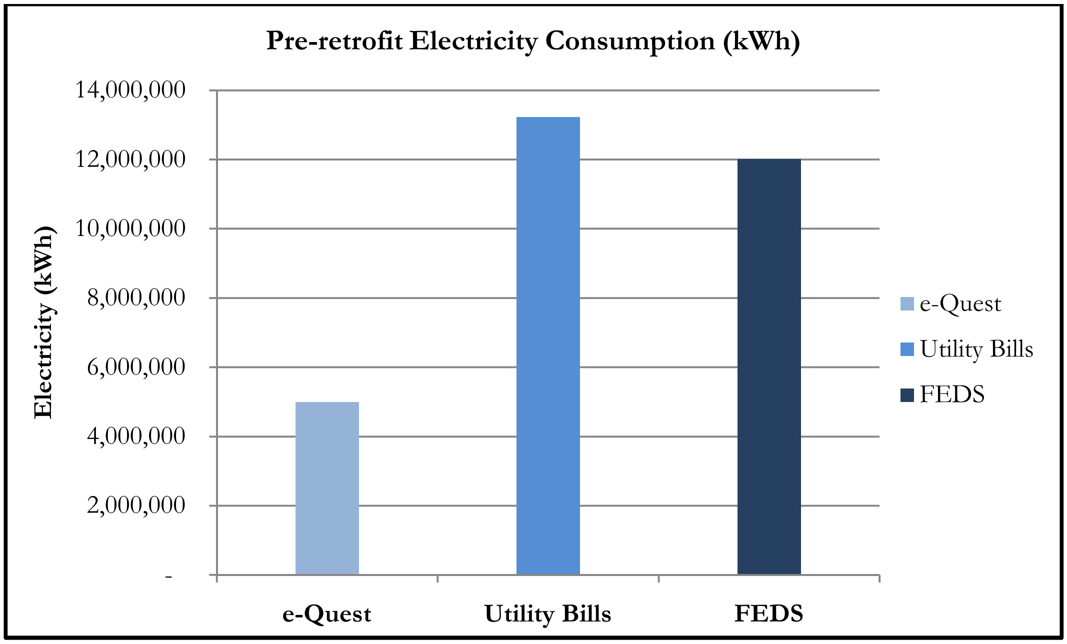


Figure 19: Pre-retrofit Electricity Consumption Comparison between e-Quest, Utility Bills and FEDS

5.4.2 Recommended Retrofits

For each of the retrofit measure suggested by FEDS, FEDS gives two or three alternatives and ranks each of them in order of the maximum LCC Savings achieved. The retrofits suggested by FEDS for the case-study building are as below:

A. Heating

Replace the existing natural gas conventional boiler with an efficiency of 80% to a conventional gas boiler –

Rank	Combustion Efficiency
1	80%
2	81.5%
3	84%

B. Lights

Replace the existing 'Exit' signs of 40 watts/fixture to electroluminescent panels or LED Retrofit Kit –

Rank	Fixture
1	Electroluminescent Panel – 0.2 W/fixture
2	Electroluminescent Panel retrofit kit – 0.35W/fixture
3	LED Retrofit kit – 2 W/fixture

C. Hot Water

Replace the existing hot water natural gas central boiler with an efficiency of 73% to a conventional gas boiler -

Rank	Combustion Efficiency
1	80%
2	81.5%
3	84%

D. Motor

Replace the existing CHW Loop Pump 150 hp Open drip proof motor with a nominal efficiency of 77% to an energy efficient 150 hp motor -

Rank	Efficiency
1	95.0%
2	96.2%

E. Motor

Replace the existing HW Loop Pump 7.5 hp Open drip proof motor with a nominal efficiency of 77% to an energy efficient 7.5 hp motor –

Rank	Efficiency
1	89.9%
2	91.0%
3	91.7%

F. Motor

Replace the existing CW Loop Pump 150 hp Open drip proof motor with a nominal efficiency of 77% to an energy efficient 150 hp motor –

Rank	Efficiency
1	95.0%
2	96.2%

G. Motor

Replace the existing cooling tower pump 100 hp Open drip proof motor with a nominal efficiency of 77% to an energy efficient 100 hp motor –

Rank	Efficiency
1	94.1%
2	95.4%
3	95.8%

5.4.3 Actual Retrofits

The two existing 900 ton Trane Centrifugal Chillers were replaced with four new 350 Ton McQuay Frictionless Centrifugal Chillers with a design rating efficiency of 0.35 kW/Ton. The piping was modified to accept the four new chillers. The new chillers primarily operate below 50% of existing kW/Ton conditions.

The central plant was re-piped from a variable primary system to a primary secondary system. This new piping configuration provides chilled water throughout the building as required by cooling demand.

The existing primary chilled & condenser water pumps were driven by 100 HP high efficiency motors with variable frequency drives. These motors and drives were upgraded along with the chiller replacement as a part of the retrofit project.

The reprogramming of existing Alerton BACNET controls is in-progress to maximize system staging and operate central plant in the most efficient manner while maintaining tenant comfort.

5.4.4 Estimated Energy Savings

The estimated annual electric-energy saving for the case-study building for the retrofits being implemented by the contractor on the basis of the e-Quest model is 1,266,200 kWh and the estimated annual natural gas saving for the case-study building is 1,166,800 kBtu.

The estimated annual electric energy saving for the case-study building for the retrofits suggested by FEDS is 1,128,564 kWh and the estimated annual natural gas saving for the case-study building as calculated by FEDS is 83,400 kBtu.

Table 23: Estimated Annual Electricity and Natural Gas Savings for Case-study Building

ESTIMATED ANNUAL SAVINGS				
	Electricity (kWh)		**Natural Gas (kBtu)**	
	FEDS	**e-Quest**	**FEDS**	**e-Quest**
Case-study Building	1,128,564	1,266,200	83,400	1,166,800

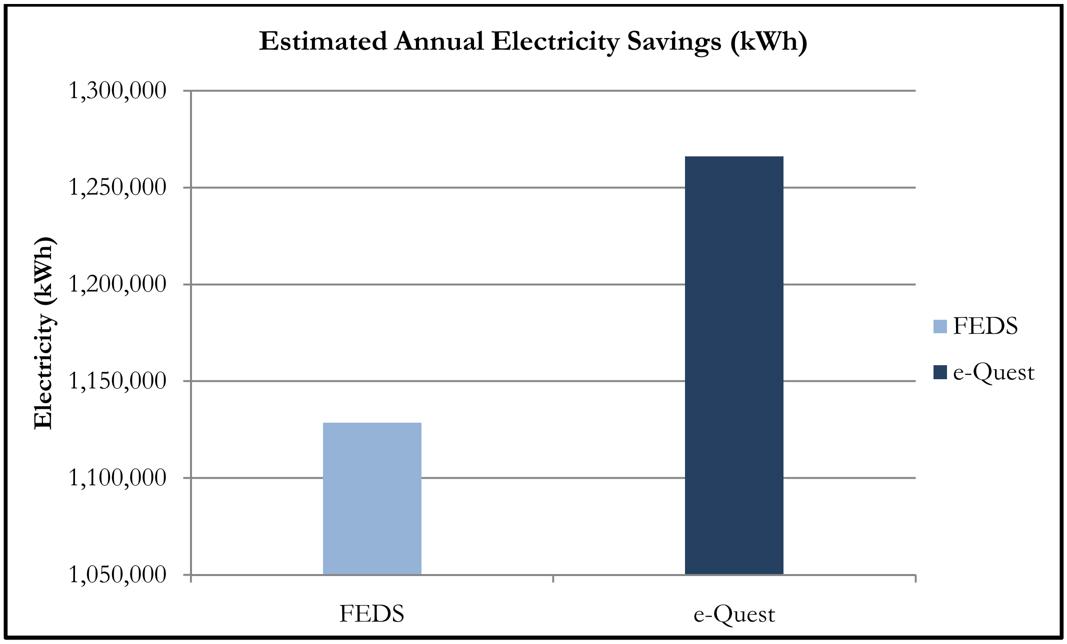


Figure 20: Estimated Annual Electricity Savings Comparison between FEDS and e-Quest for Case-study Building

The estimated annual electricity savings as calculated by both FEDS and e-Quest are almost equivalent even when the retrofits modeled in both these softwares are different. It is also observed that the estimated natural gas savings calculated by FEDS is much lower than that calculated by e-Quest, even when the retrofits modeled in FEDS include replacing a boiler which would increase the natural gas savings as compared to the retrofits modeled in e-Quest which does not have any retrofit that would directly affect the natural gas consumption.

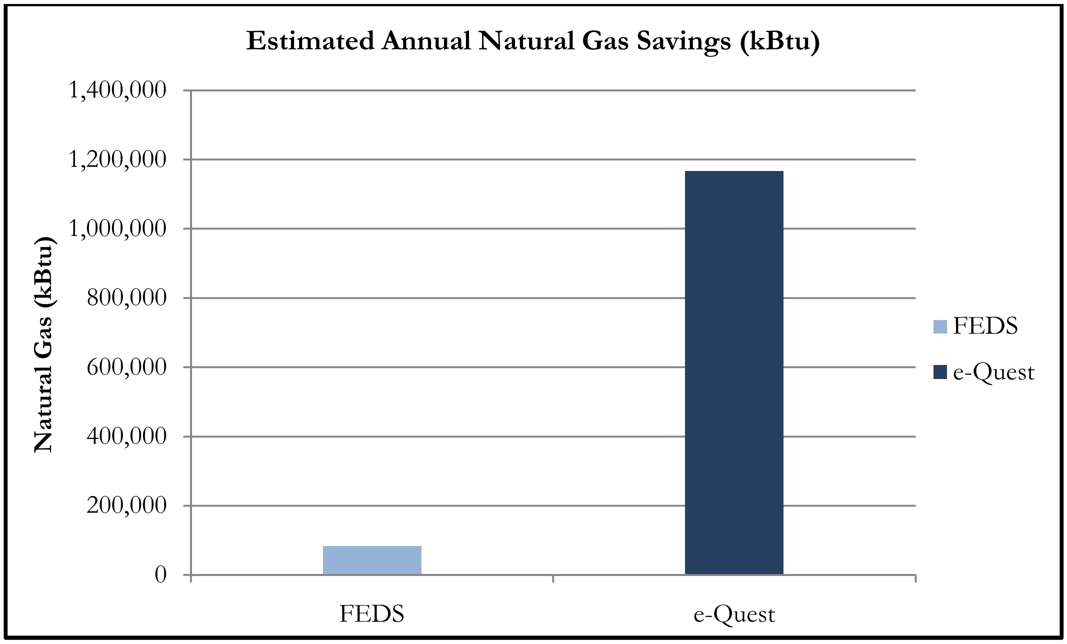


Figure 21: Estimated Annual Natural Gas Savings Comparison between FEDS and e-Quest for Case-study Building

The estimated annual savings according to the contractors' e-Quest model are higher for both electricity and natural gas, however, it should be noted that the e-Quest model from the contractor was found to be not well calibrated with the actual electricity utility data for the building.

The monthly post-retrofit electricity consumption data available from the utility bills is not sufficient to statistically predict the actual electricity savings for the facility to compare them to those estimated by FEDS and the contractors' e-Quest model.

Chapter 6

SUMMARY, CONCLUSIONS AND FUTURE WORK

6.1 Summary

Benchmarking a building for its energy use gives the facility manager and the building owner a fairly good idea about the energy use of the building and its potential for energy savings, thereby decreasing their overhead costs in terms of utility bills. Moreover, comparing the energy use of a building to its peers and giving it a rating instigates a sense of healthy competitiveness which encourages the building owners to take up energy efficiency measures and get a better rating for their businesses to stand on a higher pedestal as compared to their peers.

This research was intended to compare and analyze selected benchmarking tools such that they could be used as the first step in the audit process to encourage facility managers and building owners to audit the energy use of their facility. It also explored the usability of retrocommissioning/audit software as the next step in the audit process to help facility managers and auditors have a better idea of the building energy use and potential energy efficiency measures for the building.

The study was conducted by first applying the annual energy consumption data for the 90.1 Prototype models and the Commercial Reference Building model for Large Office building type for Phoenix (Climate zone: 2B) in Portfolio Manager and ORNL Spreadsheet to compare the Energy Use Intensities for these models and get a rating for them by comparing their EUIs to peer buildings. This formed a base to compare the EUI and rating for a Case-study large office building in Phoenix from the Energize Phoenix program using the same benchmarking tools.

The second part of this study was conducted by modeling all the Prototype models used for benchmarking in retrocommissioning/auditing software called FEDS to estimate the annual energy consumption for these prototypes, validate it by comparing to the EnergyPlus models and then analyzing the energy efficiency measures suggested by FEDS and the energy savings achieved thereof. A similar methodology was applied to the case-study building where the annual electricity consumption estimated by FEDS was compared to the e-Quest model outputs and actual pre-retrofit utility bills. The energy efficiency measure and the energy savings thereof were compared to the actual retrofits implemented on site and the estimated energy savings from the contractors' e-Quest model.

6.2 Conclusions

- The benchmarking study revealed that the EUIs progressively decreased for the Prototype models of 90.1 – 2004 to 90.1 – 2007 to 90.1 – 2010 from 46.1 to 43.0 to 33.0 kBtu/ft^2 which amounted to an approximate decrease of 7% in the 90.1 – 2007 Prototype EUI over 90.1 – 2004 Prototype EUI and an approximate decrease of 30% in the 90.1 – 2010 Prototype EUI over 90.1 – 2004 EUI.
- The ratings for the 90.1 – 2004, 90.1 – 2007 and 90.1 – 2010 Prototypes were computed to be 92, 94 and 98 respectively.
- The EUI for the Commercial Reference Building model was computed to be 62.0 Btu/ft^2 which is approximately 34% higher than the 90.1 - 2004 Prototype and hence it got a rating of 80.

- The EUI for the Case-study building pre-retrofit was calculated to be 126.2 Btu/ft^2 which is approximately 174% higher as compared to the 90.1 – 2004 Prototype model.
- The Case-study Building pre-retrofit gets a very low rating of 34. This rating is expected encourage the facility managers and the building owner to take up the energy audit process for the building.
- When the post-retrofit energy consumption data available for five months added with the pre-retrofit energy consumption data for the other seven months (to make up for a year's worth of energy consumption data) was used to benchmark the building, the EUI decreased to 119.6 Btu/ft^2 and there was an improvement in the rating from 34 to 39. The EUI is further expected to decrease and the rating increase correspondingly as more of the post-retrofit energy consumption data is available.
- The retrocommissioning/auditing study using FEDS proved that FEDS is a reasonably accurate tool to simulate a building's energy performance with some basic inputs. It was accurate in predicting the pre-retrofit electricity consumption for all prototypes when compared to the outputs from their EnergyPlus models and for the case-study building when compared to its actual pre-retrofit utility bills with an error within ±10%.
- However, it was found that FEDS is not very accurate in predicting the natural gas consumption for the prototypes when compared to the outputs from their EnergyPlus models. The estimated natural gas

consumption for the case-study building from FEDS could not be compared to actual utility data as the information was not available but was much lower as compared to the contractors' e-Quest model.

- By analyzing the energy efficiency measures suggested by FEDS, it can be concluded that FEDS is more accurate for identifying energy retrofits, as it gives alternatives for each of the retrofit suggestion and ranks them on the basis of maximum LCC savings. However, the study found that FEDS is not very suitable as a retrocommissioning tool since it does not suggest many measures to improve the operation and maintenance of the building systems to improve the energy efficiency of the building. Energy efficiency measures related to operation and maintenance would best be adjudicated by a detailed walk-thru audit of the building.

6.3 Future Work

This study could be extended to prototypes for other building typologies with different weather conditions to better analyze the natural gas consumption and savings estimates by FEDS and their contribution to the total energy consumption and savings respectively.

Complete building characteristics data from more case-study buildings could be used to analyze the retrofits suggested by FEDS and the energy savings thereof.

Also, for the case-study building used for this study, the energy savings from the FEDS recommended retrofits could better be compared and analyzed when at-least a year’s worth of actual post-retrofit energy consumption data is available for the building.

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APPENDIX A

EXAMPLES OF RECENT DEMAND-SIDE MANAGEMENT PROGRAMS IN THE U.S. DURING THE LAST 10 YEARS

(Gellings & Parmenter, 2008)

	Program Name	Implementer(s)	Time Period	Cost (Million)	Energy Savings (MWh)	Demand Savings (kW)
1. Residential Lighting Programs						
1.1	2002 California Crosscutting Statewide Residential Lighting Program	Pacific Gas & Electric Co. (PG&E); Southern California Edison (SCE); San Diego Gas & Electric Co. (SDG&E)	2002	$9.4	162,888	21,365
1.2	2002 Efficient Products Program- Lighting Component	Efficiency Vermont (EVT)	2002	$1.6	11,039	1740 - Winter 1074 - Summer
1.3	2002 Massachusetts Electric – Residential Lighting Program	Massachusetts Electric	2002	$3.3	18,037	5084
1.4	2002 Midwest Change a Light, Change the World Campaign	Midwest Energy Efficiency Alliance (MEEA)	Fall 2002	$0.63	10,198	NA
1.5	2001 Energy Star Residential Lighting Program	Northwest Energy Efficiency Alliance (NW Alliance)	2001	$2.6	271,560	NA
1.6	2000-2001 Retail Lighting Program	United Illuminating	2000 – 2001	$3.0	7808	NA
2. Residential Air-Conditioning Programs						
2.1	2002 Keep Cool Air Conditioner Bounty Program	New York State Energy Research and Development Authority (NYSERDA)	2002	NA	27,208	44,813
2.2	2002 California	PG&E; SCE; SDG&E	2002	NA[1]	8399	NA

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[1] Included in overall Single-Family Rebate Program Budget

	Statewide Single-Family Rebate Program AC Component					
2.3	2002 New Jersey Clean Energy Collaborative Residential AC Component	Conectiv Power Delivery; Jersey Central Power & Light Co. (JCP&L); Public Service Electric & Gas Co. (PSE &G); Rockland Electric Company (RECO)	2002	$24.2	NA	NA
2.4	2003 Air Conditioning Distributor Market Transformation Program	Oncor	2003	$5.9	13,478	10,800
2.5	2002 Residential Air Conditioning Program	Florida Power and Light (FPL)	2002	$18.0	78,957	37,360
3. Single – Family Comprehensive Programs						
3.1	2001 – 2002 Central Valley Hard-to-Reach Mobile Home Energy Savings Program	American Synergy Corp.	Oct. 2002 – Oct. 2003	$1.4	3,447	1,329
3.2	2002 California Statewide Single – Family Energy Efficiency Rebate Program	PG&E; SCE; SDG&E	2002	$25.9	36,028	31,869
3.3	1999-2000 Residential High Use Program	NSTAR	Aug. 1999 – Aug. 2000	$3.5	3,179	1,164 Winter 831 Summer
3.4	2001 Energy Wise Program	National Grid U.S.A.	2001	$1.2	3,461	743

3.5	2002 Efficiency Equipment Load Program	Sacramento Municipal Utility District (SMUD)	2002	$2.4	1,254	700
3.6	2002 Residential Weatherization Program	Tacoma Power	2002	$0.94	2,031	NA
4. Multi-Family Comprehensive Programs						
4.1	2002 Multi - Family Incentive Program	Austin Energy	2002	$0.58	3,121	2,080
4.2	2002 California Statewide Multi – Family Program	PG&E; SCE; SDG&E	2002	$8.3	9,050	1,853
4.3	2003 Home Energy Savings Program – Multi – Family Component	The City of Portland/Energy Trust of Oregon, Inc.	Jan – Dec 2003	$1.0	7,000	NA
4.4	2002 – 2003 Apartment & Condo Efficiency Services	Focus on Energy/Wisconsin Energy Conservation Corp. (WECC)	Sep 2002 – Aug 2003	$5.1	12,936 net	2,391 net
4.5	2002 Energy Wise Multi – Family Component	National Grid	2002	$2.3	3,487	400-winter 600 - summer
4.6	2000 Multi – Family Conservation Program	Seattle City Light (SCL)	2000	$1.2	2,769	NA
5. Audits & Information Programs						
5.1	2002 Home Performance with Energy Star Program	NYSERDA	2002	$4.0	741	80
5.2	2000 Time-of-Sale Home Inspection Program	SCE; GeoPraxis, Inc.	2000	$0.28	1,974	NA

5.3	2002 Residential Conservation Services Audit Program	National Grid	2002	$2.8	2,677	406
5.4	2002 E+ Energy Audit for Your Home Program	Northwestern Energy	2002	$1.3	4,713	884
5.5	2002 Residential Energy Advisory Services Program	SMUD	2002	$1.1	400	70
5.6	2002 California Statewide Home Energy Efficiency Program	PG&E; SCE; SDG&E	2002	$2.0	8,700	4,190
6. Residential New Construction Programs						
6.1	2001 – 2002 Austin Green Building Program	Austin Energy	FY 2000-2001	$0.60	7,666	3,630
6.2	2002 California Energy Star New Homes Program	PG&E; SCE; SDG&E	2002	$15.2	10,655	22,262
6.3	2002 New Jersey Energy Star Homes	Clean Energy for New Jersey	2002	$10.9	3,262	3,415
6.4	2002 Texas Energy Star Homes	Oncor	2002	$5.2	24,700	7,410
6.5	2002 Tucson Guarantee Home Program	Tucson Electric Power	2002	$3.0	3,023	4,094
6.6	2001 Vermont Energy Star Homes	EVT	2001	$0.92	841	278
6.7	2001-2002 Wisconsin	WECC	2002-2003	$2.9	1,049	247

	Energy Star Program					
7. Non – Residential Lighting Programs						
7.1	2003 Lighting Efficiency Program	Xcel Energy	2003	$2.3	41,780	7,896
7.2	2002-2003 Business Energy Services Team Program	KEMA - XENERGY	2002–2003	$0.94	2,704	559
7.3	2002 EZ Turnkey Program	SDG&E	2002	$1.3	3,121	570
7.4	2003 Small Commercial Prescriptive Lighting Initiative	SMUD	2003	$2.7	19,865	3,920
7.5	2002 Small Business Energy Advantage Program	Connecticut Light & Power (CL&P)	2003	$4.6	16,167	3,570
7.6	2002 California Statewide Express Efficiency Program	PG&E; SCE; SDG&E	2002	$21.7	244,346	43,000
8. Non – Residential HVAC Programs						
8.1	New England Efficiency Partnership (NEEP) Cool Choice Program	CL&P; United Illuminating; Cape Light Compact; Massachusetts Electric Co.; Nantucket Electric Co.; NSTAR Electric; Western Massachusetts Electric Co.; Conectiv Power Delivery; JCP&L; PSE&G; Narragansett Electric Co.; Burlington Electric; EVT	2002	$2.3	3,929	3,518
8.2	Avista Rooftop	Avista Utilities	2001	$1.8	13,000	NA

	HVAC Maintenance Program					
8.3	California Express Efficiency HVAC Component	PG&E; SCE; SDG&E	2002	NA[2]	2,901	NA
8.4	Los Angeles Department of Water and Power (DWP) Chiller Efficiency	Los Angeles DWP	2003-2004	$0.786	7,174	5,666
8.5	FP&L Commercial/ Industrial HVAC Program	FPL	2002	$5.4	NA	NA
8.6	Glendale Water and Power Check Me!	Glendale Water and Power	2001	$0.150	25,128	358
9. Non – Residential Large Comprehensive Incentive Programs						
9.1	Non-Residential Standard Performance Contract	PG&E; SCE; SDG&E	2002	$23.0	167,300	28,441
9.2	Energy $mart C/I Performance	NYSERDA	2001-2002	$34.2	204,500	53,886
9.3	Energy Opportunities	United Illuminating	2002	$1.3	10,772	2,627
9.4	Power Smart	BC Hydro	2004	$25.0	128,000	NA
9.5	Custom Efficiency	Xcel Energy (Colorado)	2002-2005	$12.2	76,167	40,077
9.6	Custom Services	CL&P	2003	$8.6	24,853	NA
9.7	Energy Initiative	National Grid	2002	$9.7	30,862	6,089
9.8	Energy Shared	WP&L (Alliant)	2001	$21.9	104,325	16,000

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[2] Included in overall Express Efficiency program budget

	Savings	Wisconsin				
9.9	Business Energy Services	EVT	2002	$1.1	4,955	NA
9.10	Commercial & Industrial Custom Retrofit	SMUD	2002	$7.3	NA	NA
10. New Construction Information & Services Programs						
10.1	Energy Conscious Construction	Northeast Utilities	2002	$7.4	33,365	NA
10.2	Energy Design Assistance	Xcel Energy	2002	$3.4	63,093	19,100
10.3	Design 2000 Plus	National Grid	2002	$13.9	31,804	6,429
10.4	Savings by Design	PG&E; SCE; SDG&E	2002	$22.6	82,697	18,600
10.5	Construction Solutions	NSTAR	2001	$7.9	14,230	1,710
10.6	Commercial & Industrial New Construction Program	Hawaiian Electric Co. (HECO)	1999	$0.935	5,584	821

APPENDIX B

DETAILED DESCRIPTION OF COMMERCIAL REFERENCE BUILDING PROTOTYPE MODEL

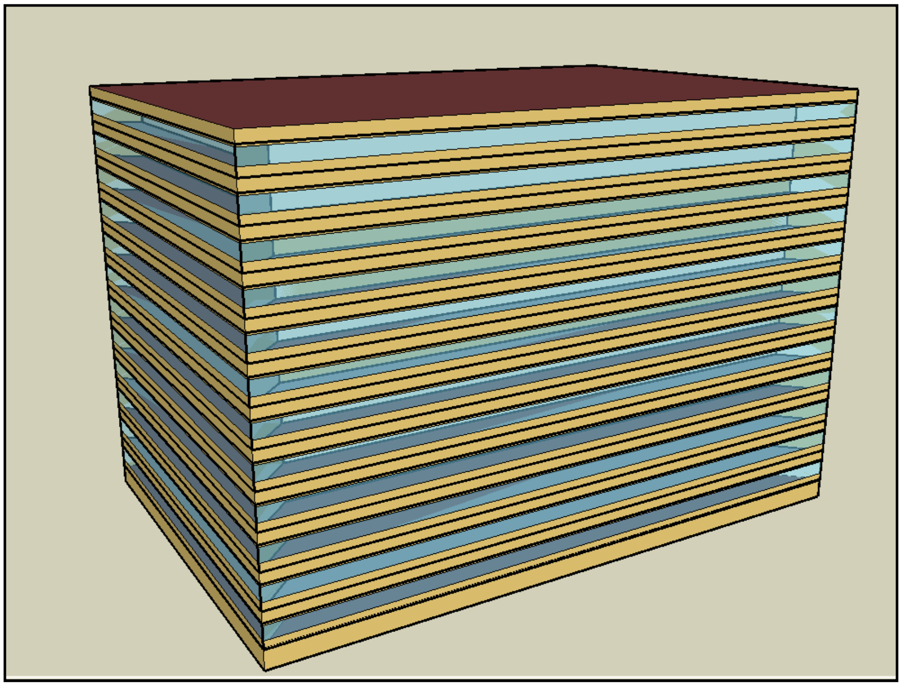


Figure 22: Commercial Reference Building model for Large Office - Post 1980 construction

Building Summary

Program

Building Name	Reference Building Large Office Post-1980
Available Fuel Types	Gas, Electricity
Principal Building Activity	Office

Form

Total Floor Area (m^2)	46,320
Building Shape	Rectangle
Aspect Ratio	1.5

Number of Floors	12 plus basement
Window Fraction (Window to Wall Ratio)	
South	0.38
East	0.38
North	0.38
West	0.38
Total	0.38
Skylight/TDD Percentage	0.0
Shading Geometry	None
Azimuth	0.0
Thermal Zoning	Core zone with four perimeter zones on each floor
Floor to Ceiling Height (m)	2.74
Floor to Floor Height (m)	3.96
Roof type	Built-up flat roof, insulation entirely above deck

Fabric

Exterior walls

Construction Type	Mass wall
Gross Dimensions - Total Area (m^2)	11,590
Net Dimensions - Total Area (m^2)	6,954
Wall to Skin Ratio	0.77

Roof	
Construction Type	IEAD
Gross Dimensions - Total Area (m^2)	3,563
Net Dimensions - Total Area (m^2)	3,563
Roof to Skin Ratio	0.24
Window Dimensions (m^2)	
South	1,391
East	927
North	1,391
West	927
Total Area (m^2)	4,636
Operable area (m^2)	0
Foundation	
Foundation Type	Basement
Construction	4 in slab w/carpet
Dimensions - Total Area (m^2)	3,563
Interior Partitions	
Construction	2x4 steel-frame with gypsum board
Dimensions - Total Area (m^2)	8,524
Internal Mass	
Construction	15 cm wood
Dimensions - Total Area (m^2)	92,641

Thermal diffusivity (m^2/s)	1.84E-07
Air Barrier System	
Infiltration (ACH)	0.36

HVAC

System Type	MZ-VAV
Heating Type	Gas boiler
Cooling Type	2 Water cooled chillers
Fan Control	Variable
Service Water Heating	
SWH Type	Boiler
Fuel	Gas
Thermal Efficiency (%)	78
Temperature Set point (ºC)	60
Water Consumption (m^3)	1,504.13

Zone Summary

Total Conditioned Zones	
Area (m^2)	46,320
Volume (m^3)	178,146
Gross Wall Area (m^2)	11,590
Window Glass Area (m^2)	4,636
People	2,397

SWH (L/h)	968
Ventilation Total (L/s)	23,973

Location Summary

Program	
ASHRAE 90.1-2004 Climate Zone	2B
Available Fuel Types	Gas, Electricity
Fabric	
Exterior walls	
Construction Type	Mass wall
R-value (m^2·K/W)	0.43
Underground walls	
Construction Type	8in concrete
R-value (m^2·K/W)	0.31
Roof	
Construction Type	IEAD
R-value (m^2·K/W)	3.83
Window	
U-Factor (W/m^2·K)	5.84
SHGC	0.25
Visible transmittance	0.11
Foundation	
Foundation Type	Basement

Construction	4 in slab w/carpet
R-value ($m^2 \cdot K/W$)	0.54

HVAC

HVAC Sizing

Air Conditioning (kW)	
COOLSYS1 CHILLER 1	1,674.24
COOLSYS1 CHILLER 2	1,688.81
Heating (kW)	
HEATSYS1 BOILER	3,128.97

HVAC Efficiency

Air Conditioning (COP)	
COOLSYS1 CHILLER 1	5.200
COOLSYS1 CHILLER 2	5.200
Heating Efficiency (%)	0.70

HVAC Control - Economizer

VAV_1_FAN	Differential Dry Bulb
VAV_2_FAN	Differential Dry Bulb
VAV_3_FAN	Differential Dry Bulb
VAV_5_FAN	Differential Dry Bulb

Fan Max Flow Rate (m^3/s)

VAV_1_FAN	18.83
VAV_2_FAN	196.39

VAV_3_FAN	19.62
VAV_5_FAN	8.10

Utility Costs

Electric Utility Rates

Average Annual Rate ($/kWh)	0.07210
Total Cost ($/$m^2$)	19.37

Gas Utility Rates

Average Annual Rate ($/MJ)	0.00819
Total Cost ($/$m^2$)	0.30

Total Utility Costs

Cost Intensity ($/$m^2$)	13.65

APPENDIX C

DETAILED DESCRIPTION OF 90.1 PROTOTYPES MODELS

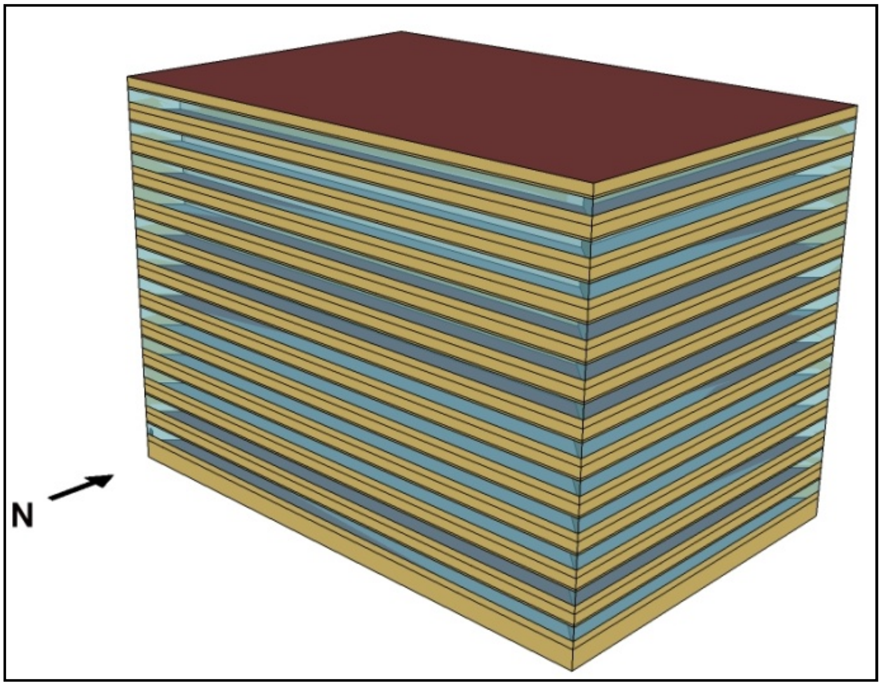


Figure 23: 90.1 Prototypes for Large Office Building

Program

Location Zone	2B: Phoenix (hot, dry)
Available fuel types	Gas, Electricity
Building Type	Office
Building Prototype	Large Office

Form

Total Floor Area (sq feet)	498,600 (240 x 160)
Aspect Ratio	1.5
Number of Floors	12 (plus basement)
Window Fraction	40% of above-grade gross walls
	37.5% of gross walls

Window Locations	Even distribution among all four sides
Shading Geometry	None
Azimuth	Non-directional
Thermal Zoning	Perimeter zone depth: 15 ft. Each floor has four perimeter zones and one core zone. Percentages of floor area: Perimeter 33%, Core 67%
Floor to floor height (feet)	13
Floor to ceiling height (feet)	9
Glazing sill height (feet)	3

Architecture

Exterior walls

Construction	Mass (pre-cast concrete panel): 8 in. Heavy-Weight Concrete + Wall Insulation + 0.5 in. gypsum board
U-factor (Btu / h * ft^2 * °F)	ASHRAE 90.1 Requirements Nonresidential; Walls, Above-Grade, Steel-Framed
Dimensions	Based on floor area and aspect ratio

Tilts and orientations	Vertical

Roof

Construction	Built-up Roof: Roof membrane + Roof insulation + metal decking
U-factor (Btu / h * ft^2 * °F)	ASHRAE 90.1 Requirements Nonresidential; Roofs, Insulation entirely above deck
Dimensions	Based on floor area and aspect ratio
Tilts and orientations	Horizontal

Window

Dimensions	Based on window fraction, location, glazing sill height, floor area and aspect ratio
Glass-Type and frame	Hypothetical window with the U-factor and SHGC shown below
U-factor (Btu / h * ft2 * °F)	ASHRAE 90.1 Requirements Nonresidential

Operable area	0%
Foundation	
Foundation Type	Basement (unconditioned)
Construction	8" concrete wall; 6" concrete slab, 140 lbs heavy-weight aggregate
Thermal properties for ground floor	ASHRAE 90.1 Requirements
U-factor (Btu / h * ft2 * °F)	Nonresidential; Floors, Mass
Thermal properties for basement	No insulation
Dimensions	Based on floor area and aspect ratio
Interior Partitions	
Construction	2 x 4 uninsulated stud wall
Dimensions	Based on floor plan and floor-to-floor height
Internal Mass	6 inches standard wood (16.6 lb/ft^2)

Air Barrier System

Infiltration	Peak: 0.2016 cfm/sf of above grade exterior wall surface area (when fans turn off)

HVAC

System Type

Heating type	Gas boiler
Cooling type	Two water-cooled centrifugal chillers
Distribution and terminal units	VAV terminal box with damper and hot-water reheating coil Zone control type: minimum supply air at 30% of the zone design peak supply air

HVAC Sizing

Air Conditioning	Auto-sized
Heating	Auto-sized

HVAC Efficiency

Air Conditioning	Varies by climate locations based on cooling capacity
Heating	Varies by climate locations based on cooling capacity

HVAC Control

Thermostat Setpoint	75°F Cooling/70°F Heating
Thermostat Setback	85°F Cooling/60°F Heating
Supply air temperature	Maximum 110°F, Minimum 52°F
Chilled water temperatures	44 °F
Hot water temperatures	180 °F
Economizers	Air-side economizer

Supply Fan

Supply Fan Efficiency	60% to 62%

Pump

Pump Type	CHW and HW: variable speed; CW: constant speed
Rated Pump Head	CHW: 56 ft; HW and CW: 60 ft
Pump Power	Auto-sized

Cooling Tower

Cooling Tower Type	Open cooling tower with 2-speed fans
Cooling Tower Power	Auto-sized

Service Water Heating

SWH type	Storage Tank
Fuel type	Natural Gas
Thermal efficiency	80%
Tank Volume (gal)	260
Water temperature	180 F

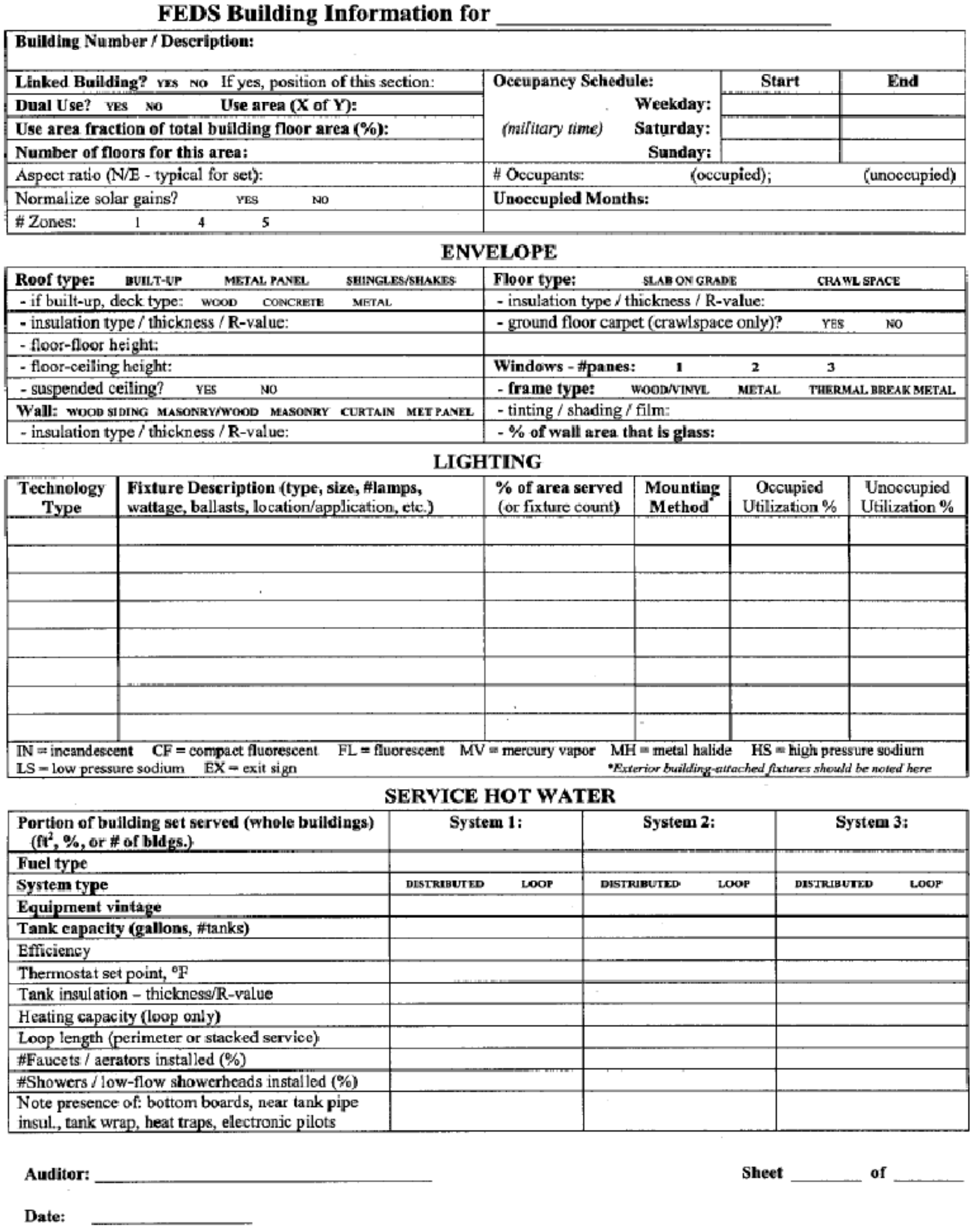
Zone Summary

Area (ft^2)	498407.8
Volume (ft^3)	6287267.6
Gross Wall Area (ft^2)	124705.4
Window Glass Area (ft^2)	49884.2
Lighting (W/ft^2)	1.0
People (ft^2/person)	199.9
Number of People	2493.0
Plug and Process (W/ft^2)	0.727

APPENDIX D

FEDS DATA COLLECTION FORM

The following form used to collect FEDS input data during building audits has been adapted from the *PNNL - FEDS Assessment Report 2005*. All the data types indicated on this form may not be applicable to all the buildings and all the information on this form is not required; where necessary the FEDS model infers the values for missing data based on other known building characteristics.



FEDS Building Information for ____________________________

Building Number / Description:			
Linked Building? YES NO If yes, position of this section:	**Occupancy Schedule:**	**Start**	**End**
Dual Use? YES NO **Use area (X of Y):**	**Weekday:**		
Use area fraction of total building floor area (%):	*(military time)* **Saturday:**		
Number of floors for this area:	**Sunday:**		
Aspect ratio (N/E - typical for set):	# Occupants: (occupied); (unoccupied)		
Normalize solar gains? YES NO	**Unoccupied Months:**		
# Zones: 1 4 5			

ENVELOPE

Roof type: BUILT-UP METAL PANEL SHINGLES/SHAKES	**Floor type:** SLAB ON GRADE CRAWL SPACE
- if built-up, deck type: WOOD CONCRETE METAL	- insulation type / thickness / R-value:
- insulation type / thickness / R-value:	- ground floor carpet (crawlspace only)? YES NO
- floor-floor height:	
- floor-ceiling height:	**Windows - #panes:** 1 2 3
- suspended ceiling? YES NO	- **frame type:** WOOD/VINYL METAL THERMAL BREAK METAL
Wall: WOOD SIDING MASONRY/WOOD MASONRY CURTAIN MET PANEL	- tinting / shading / film:
- insulation type / thickness / R-value:	**- % of wall area that is glass:**

LIGHTING

Technology Type	**Fixture Description (type, size, #lamps, wattage, ballasts, location/application, etc.)**	**% of area served** (or fixture count)	**Mounting Method***	Occupied Utilization %	Unoccupied Utilization %

IN = incandescent CF = compact fluorescent FL = fluorescent MV = mercury vapor MH = metal halide HS = high pressure sodium
LS = low pressure sodium EX = exit sign **Exterior building-attached fixtures should be noted here*

SERVICE HOT WATER

Portion of building set served (whole buildings) (ft^2, %, or # of bldgs.)	**System 1:**	**System 2:**	**System 3:**
Fuel type			
System type	DISTRIBUTED LOOP	DISTRIBUTED LOOP	DISTRIBUTED LOOP
Equipment vintage			
Tank capacity (gallons, #tanks)			
Efficiency			
Thermostat set point, °F			
Tank insulation – thickness/R-value			
Heating capacity (loop only)			
Loop length (perimeter or stacked service)			
#Faucets / aerators installed (%)			
#Showers / low-flow showerheads installed (%)			
Note presence of: bottom boards, near tank pipe insul., tank wrap, heat traps, electronic pilots			

Auditor: ______________________ **Sheet** _______ **of** _______

Date: ______________

HVAC

Portion of building set <u>NOT</u> heated (ft^2, %, or # of bldgs.)	**HEATING**		
Portion of building set served by this heating type (whole buildings) (sq. ft, percent, or number of buildings)	**Type 1:**	**Type 2:**	**Type 3:**
Fuel type			
Equipment type: 0=Elec. resistance baseboard 1=Forced air furnace 2=Air-source heat pump 3=Ground-coupled heat pump 4=Radiator/central steam/hot water 5=Fan coils/central steam/hot water/electricity 6=AHU/central steam/hot water 7=Radiator/single building boiler 8=Fan coils/single building boiler 9=AHU/single building boiler			
Output capacity (total per building)			
Number of pieces of equipment			
Efficiency (%)			
Equipment vintage			
Thermostat set point(s), °F			
Ventilation control mode: 0=cycle 1=constant 2=constant occupied hours/cycle unoccupied hours 3=constant occupied hours/off unoccupied hours 4=no mechanical ventilation			
Ventilation supply air (cfm)			
Outdoor air (NONE, 100%, OTHER?)			
Total fan motor capacity (hp or kW)			
Desiccant dehumidification (and heat source)?			
Portion of building set <u>NOT</u> cooled (ft^2, %, or # of bldgs.)	**COOLING**		
Portion of building set served by this equipment type (whole buildings) (ft^2, %, or # of bldgs.)	**Type 1:**	**Type 2:**	**Type 3:**
Fuel / Equip. type: 0 = evap. cooler 1 = window/wall units 2 = air heat pump 3 = water heat pump 4 = package or split DX 5 = fan coil/conv. chiller 6 = AHU/conv. chiller 7 = fan coil/absorp. chiller 8 = AHU/absorp. chiller 9 = fan coil/central chilled water 10 = AHU/central chilled water			
Output capacity (total per building)			
Number of units			
Nominal COP			
Cooling equipment vintage			
Thermostat set point(s), °F			

MISC. EQUIPMENT

	Type 1:	**Type 2:**	**Type 3:**	**Type 4:**
Type & Fuel				
Capacity				
Occupied utilization				
Unoccupied utilization				

MOTORS

	Type 1:	**Type 2:**	**Type 3:**	**Type 4:**
Horsepower				
# Motors of this type				
Occupied utilization				
Unoccupied utilization				
Other nameplate data				

NOTES

APPENDIX E

FEDS RETROFIT OPTIONS

(PNNL, 2008)

The retrofit options for the FEDS software are listed below. This list is continually expanded and refined as new functionality is added to the software. Notes on specific end uses are presented below under each category.

E.1 Heating Retrofit Alternatives

The available heating retrofit alternatives are listed below. Both equipment replacements and add-on technologies are considered for building-level heating systems. For central district heating systems, the only retrofit options involve conversion to a building-level centralized system.

Electric Resistance

Replace electric baseboard units with

- Electric infrared heating system
- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

Replace electric furnaces with

- Newer conventional electric furnace
- Conventional distillate oil furnace
- Conventional gas furnace (80, 84% efficiencies)
- Condensing gas furnace (90, 92% efficiencies)
- Conventional LPG furnace (80, 84% efficiencies)

- Condensing LPG furnace (90, 92% efficiencies)
- Electric infrared heating system
- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

Replace electric infrared heating system with

- Newer electric infrared heating system
- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

Replace electric boiler (serving air handlers, fan coils, radiators, or radiant heat system) with

- New conventional distillate oil boiler (83, 84, 86.5% combustion efficiencies)
- New conventional residual oil boiler (82, 83.5, 86% combustion efficiencies)
- New conventional gas boiler (80, 81.5, 84% combustion efficiencies)
- Gas pulse condensing boiler (87, 91% combustion efficiencies)
- New conventional LPG boiler (80, 81.5, 84% combustion efficiencies)
- LPG pulse condensing boiler (87, 91% combustion efficiencies)

- Electric infrared heating system
- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

District Systems

Replace district steam (serving air handlers, fan coils, radiators, or radiant heat system) with

- Conventional distillate oil boiler (83, 84, 86.5% combustion efficiencies)
- Conventional residual oil boiler (82, 83.5, 86% combustion efficiencies)
- Conventional gas boiler (80, 81.5, 84% combustion efficiencies)
- Gas pulse condensing boiler (87, 91% combustion efficiencies)
- Conventional LPG boiler (80, 81.5, 84% combustion efficiencies)
- LPG pulse condensing boiler (87, 91% combustion efficiencies)
- Electric infrared heating system
- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

Retrofits considered are switching from steam supplied by the thermal loop to steam supplied by a single-building boiler. Fuel-switching alternatives are considered only when the fuel is available to the building set.

Replace district hot water (serving air handlers, fan coils, radiators, or radiant heat system) with

- Conventional distillate oil boiler (83, 84, 86.5% combustion efficiencies)
- Conventional residual oil boiler (82, 83.5, 86% combustion efficiencies)
- Conventional gas boiler (80, 81.5, 84% combustion efficiencies)
- Gas pulse condensing boiler (87, 91% combustion efficiencies)
- Conventional LPG boiler (80, 81.5, 84% combustion efficiencies)
- LPG pulse condensing boiler (87, 91% combustion efficiencies)
- Electric infrared heating system
- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

Oil/Gas/Coal/Other

Replace existing (oil, natural gas, coal, other fuel) boiler (serving air handlers, fan coils, radiators, or radiant heat system) with

- New conventional distillate oil boiler (83, 84, 86.5% combustion efficiencies)
- New conventional residual oil boiler (82, 83.5, 86% combustion efficiencies)
- New conventional gas boiler (80, 81.5, 84% combustion efficiencies)
- Gas pulse condensing boiler (87, 91% combustion efficiencies)

- New conventional LPG boiler (80, 81.5, 84% combustion efficiencies)
- LPG pulse condensing boiler (87, 91% combustion efficiencies)
- Electric infrared heating system
- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

Or add:

- Feedwater economizers
- Automatic electric damper

Fuel switching alternatives are only considered when the fuel is available to the building set. Performance of existing boiler depends on age, size, and fuel type. Electric dampers only considered as options for natural draft boilers.

Replace existing (oil, natural gas, other fuel) furnace with

- Conventional electric furnace
- Conventional distillate oil furnace
- Conventional gas furnace (80, 84% efficiencies)
- Condensing gas furnace (90, 92% efficiencies)
- Conventional LPG furnace (80, 84% efficiencies)
- Condensing LPG furnace (90, 92% efficiencies)
- Electric infrared heating system

- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

Fuel-switching alternatives are only considered when the fuel is available to the building set. Performance of existing furnace depends on age, size, and fuel type.

Replace existing (oil, natural gas, LPG) infrared heating system with

- Electric infrared heating system
- Natural gas infrared heating system (standard, medium, or high efficiency)
- LPG infrared heating system (standard, medium, or high efficiency)

Fuel-switching alternatives are only considered when the fuel is available to the building set. Performance of existing infrared system depends on age, size, and fuel type.

Heat Pumps or Heat/Cool Pairs

Replace existing heat/cool pair (separate heat and cool equipment) with

- Individual heat and/or cool technologies
- Electric air source heat pump
- Dual-fuel air source heat pump with integrated natural gas backup heat
- Dual-fuel air source heat pump with integrated LPG backup heat
- Horizontal closed-loop ground-coupled heat pump system
- Vertical closed-loop ground-coupled heat pump system
- Open-loop ground-coupled heat pump system

- Packaged a/c unit with integral natural gas heat
- Packaged a/c unit with integral LPG heat
- Packaged a/c unit with natural gas heat and chlorine-free refrigerant
- Packaged a/c unit with LPG heat and chlorine-free refrigerant

Replace existing heat/cool pair (separate heat and cool equipment; heat is a furnace) with

- Individual heat and/or cool technologies
- Electric air source heat pump
- Dual-fuel air source heat pump with integrated natural gas backup heat
- Dual-fuel air source heat pump with integrated LPG backup heat
- Horizontal closed-loop ground-coupled heat pump system
- Vertical closed-loop ground-coupled heat pump system
- Open-loop ground-coupled heat pump system
- Packaged a/c unit with integral natural gas heat
- Packaged a/c unit with integral LPG heat
- Packaged a/c unit with natural gas heat and chlorine-free refrigerant
- Packaged a/c unit with LPG heat and chlorine-free refrigerant
- Or add electric air source heat pump plus controls for dual-fuel operation.

Replace existing heat/cool pair (integrated heat and cool equipment) with

- Electric air source heat pump
- Dual-fuel air source heat pump with integrated natural gas backup heat

- Dual-fuel air source heat pump with integrated LPG backup heat
- Horizontal closed-loop ground-coupled heat pump system
- Vertical closed-loop ground-coupled heat pump system
- Open-loop ground-coupled heat pump system
- Packaged a/c unit with integral natural gas heat
- Packaged a/c unit with integral LPG heat
- Packaged a/c unit with natural gas heat and chlorine-free refrigerant
- Packaged a/c unit with LPG heat and chlorine-free refrigerant

Replace existing electric air source heat pump with

- Newer, more efficient electric air source heat pump
- Dual-fuel air source heat pump with integrated natural gas backup heat
- Dual-fuel air source heat pump with integrated LPG backup heat
- Horizontal closed-loop ground-coupled heat pump system
- Vertical closed-loop ground-coupled heat pump system
- Open-loop ground-coupled heat pump system
- Or add furnace (gas, distillate oil, LPG) to existing heat pump plus controls for dual-fuel operation.

Replace existing natural gas engine-driven air source heat pump with

- Electric air source heat pump
- Dual-fuel air source heat pump with integrated natural gas backup heat

- Dual-fuel air source heat pump with integrated LPG backup heat
- Horizontal closed-loop ground-coupled heat pump system
- Vertical closed-loop ground-coupled heat pump system
- Open-loop ground-coupled heat pump system

Replace existing dual-fuel air source heat pump (integrated backup heat) with

- Electric air source heat pump
- Newer, more efficient dual-fuel air source heat pump with integrated natural gas backup heat
- Newer, more efficient dual-fuel air source heat pump with integrated LPG backup heat
- Horizontal closed-loop ground-coupled heat pump system
- Vertical closed-loop ground-coupled heat pump system
- Open-loop ground-coupled heat pump system
- Or adjust crossover temperature of existing dual-fuel heat pump

Replace existing dual-fuel air source heat pump (separate backup heat) with

- Electric air source heat pump
- Dual-fuel air source heat pump with integrated natural gas backup heat
- Dual-fuel air source heat pump with integrated LPG backup heat
- Horizontal closed-loop ground-coupled heat pump system
- Vertical closed-loop ground-coupled heat pump system

- Open-loop ground-coupled heat pump system

Or replace:

- Furnace of dual-fuel heat pump system with newer, more efficient furnace
- Heat pump of dual-fuel heat pump system with newer, more efficient air source heat pump

Or adjust crossover temperature of existing dual-fuel heat pump

Replace water source heat pump units of an existing ground-coupled heat pump system

E.2 Cooling Retrofit Alternatives

The available cooling retrofit alternatives are listed below. Replacement technologies are considered for both building-level and district cooling systems.

Replace package units (cooled air output) with

- Newer, more efficient window/through-wall AC units (<1.5 tons cooling)
- Newer, more efficient split system residential AC units (1.5 to 5.4 tons cooling)
- Newer, more efficient single zone packaged AC units (1.5 to 20 tons cooling)

- Newer, more efficient multi-zone packaged AC units (20 to 150 tons cooling)

Replace window/through-wall package AC units or other DX cooling with

- Air-cooled electric chiller with fan coils
- Water-cooled reciprocating electric chiller with fan coils and cooling tower
- Water-cooled centrifugal electric chiller with fan coils and cooling tower

Replace single building air-cooled electric chiller (chilled water output) with

- Newer, more efficient air-cooled electric chiller
- Water-cooled reciprocating electric chiller and cooling tower
- Water-cooled centrifugal electric chiller and cooling tower
- Air-cooled gas engine-driven chiller
- Water-cooled gas engine-driven chiller and cooling tower
- Single building double-effect absorption chiller (natural gas or LPG) and cooling tower

Replace single building water-cooled electric chiller (chilled water output) with

- Newer, more efficient water-cooled electric chiller
- Water-cooled gas engine-driven chiller
- Water-cooled gas engine-driven chiller and cooling tower

- Single building double-effect absorption chiller (natural gas or LPG)

Replace single building air-cooled natural gas engine-driven chiller (chilled water output) with

- Air-cooled conventional electric chiller
- Water-cooled reciprocating electric chiller and cooling tower
- Water-cooled centrifugal electric chiller and cooling tower
- Newer, more efficient air-cooled natural gas engine-driven chiller
- Water-cooled gas engine-driven chiller and cooling tower
- Single building double-effect absorption chiller (natural gas or LPG) and cooling tower

Replace single building water-cooled natural gas engine-driven chiller (chilled water output) with

- Water-cooled reciprocating electric chiller
- Water-cooled centrifugal electric chiller
- Newer, more efficient water-cooled natural gas engine-driven chiller
- Single building double-effect absorption chiller (natural gas or LPG)

Replace single building air-cooled absorption chiller (fuels include: steam, high-temperature hot water, natural gas, and LPG – chilled water output) with

- Air-cooled conventional electric chiller

- Water-cooled reciprocating electric chiller and cooling tower
- Water-cooled centrifugal electric chiller and cooling tower
- Air-cooled natural gas engine-driven chiller
- Water-cooled gas engine-driven chiller and cooling tower
- Single-Stage Absorption Chiller (steam or high-temperature hot water)
- Single building double-effect absorption chiller (steam, natural gas, or LPG) and cooling tower

Replace district chilled water with

- Air-cooled electric chiller
- Water-cooled reciprocating electric chiller and cooling tower
- Water-cooled centrifugal electric chiller and cooling tower
- Air-cooled gas engine-driven chiller
- Water-cooled gas engine-driven chiller and cooling tower
- Single building double-effect absorption chiller (natural gas or LPG) and cooling tower

Retrofits considered are switching from district chilled water to chilled water supplied by a single building chiller.

Heat Pumps or Heat/Cool Pairs

Refer to the discussion of heating retrofit alternatives for a list of possible retrofits for heat pumps and heat/cool pairs.

E.3 Envelope Retrofit Alternatives

The following retrofits are available for roof, walls, floor, and windows:

Roof/Ceiling Insulation (type depends on roof type)

- Attic Ceiling: Increase insulation by R-13
- Attic Ceiling: Increase insulation by R-19
- Attic Ceiling: Increase insulation by R-22
- Attic Ceiling: Increase insulation by R-30
- Attic Ceiling: Increase insulation by R-38
- Suspended Ceiling: Increase insulation by R-11
- Suspended Ceiling: Increase insulation by R-19
- Suspended Ceiling: Increase insulation by R-30
- Suspended Ceiling: Increase insulation by R-38
- Insulate Built-up Roof Surface (R-5) and Re-Roof
- Insulate Built-up Roof Surface (R-10) and Re-Roof
- Insulate Built-up Roof Surface (R-15) and Re-Roof
- Insulate Built-up Roof Surface (R-20) and Re-Roof
- Add Insulation to Interior Surface of Metal Roof: 2 inches Fiberglass
- Add Insulation to Interior Surface of Metal Roof: 3 inches Fiberglass
- Add Insulation to Interior Surface of Metal Roof: 4 inches Fiberglass
- Add Insulation to Interior Surface of Metal Roof: 2-layer Reflective Bubble Pack
- Add Insulation to Interior Surface of Metal Roof: 1 inch Foam

- Add Insulation to Interior Surface of Metal Roof: 2 inches Foam

Wall Insulation (applicability of retrofit depends on wall construction material, presence of existing insulation, and space available)

- Blow-in Insulation to Fill Available Space
- Interior Masonry Surface: Increase insulation by R-4.1
- Interior Masonry Surface: Increase insulation by R-8.3
- Interior Masonry Surface: Increase insulation by R-10.3
- Interior Masonry Surface: Increase insulation by R-12.4
- Add Interior Metal Wall Surface Insulation: 2 inches Fiberglass
- Add Interior Metal Wall Surface Insulation: 3 inches Fiberglass
- Add Interior Metal Wall Surface Insulation: 4 inches Fiberglass
- Add Interior Metal Wall Surface Insulation: 2-layer Reflective Bubble Pack
- Add Interior Metal Wall Surface Insulation: 1 inch Foam
- Add Interior Metal Wall Surface Insulation: 2 inches Foam

Floor Insulation (type depends on floor type)

- Insulate above Crawlspace: Increase insulation by R-11
- Insulate above Crawlspace: Increase insulation by R-19
- Insulate above Crawlspace: Increase insulation by R-30
- Insulate above Crawlspace: Increase insulation by R-38

- Insulate Perimeter of Slab on Grade: Increase insulation by R-5
- Insulate Perimeter of Slab on Grade: Increase insulation by R-7.5
- Insulate Perimeter of Slab on Grade: Increase insulation by R-10
- Insulate Perimeter of Slab on Grade: Increase insulation by R-15

Window Retrofits

- Add Storm Windows
- Add Retrofit Film
- Install Aluminum Frame Double Pane Window
- Install Aluminum Frame Double Pane Low-E Window
- Install Aluminum Frame Double Pane Super Low-E Window
- Install Aluminum Frame Double Pane Argon/Low-E Window
- Install Aluminum Frame Double Pane Argon/Super Low-E Window
- Install Thermal Break Aluminum Frame Double Pane Window
- Install Thermal Break Aluminum Frame Double Pane Low-E Window
- Install Thermal Break Aluminum Frame Double Pane Super Low-E Window
- Install Thermal Break Aluminum Frame Double Pane Argon/Low-E Window
- Install Thermal Break Aluminum Frame Double Pane Argon/Super Low-E Window

- Install Thermal Break Aluminum Frame Double Pane Heat Mirror Window
- Install Wood or Vinyl Frame Double Pane Window
- Install Wood or Vinyl Frame Double Pane Low-E Window
- Install Wood or Vinyl Frame Double Pane Super Low-E Window
- Install Wood or Vinyl Frame Double Pane Argon/Low-E Window
- Install Wood or Vinyl Frame Double Pane Argon/Super Low-E Window

E.4 Service Hot Water Retrofit Alternatives

All logical combinations of the retrofits listed below are also included:

Distributed Systems

Replace distributed tank system (electric, gas, oil, other fuels) with

- electric resistance water heater (R-16 insulation)
- electric resistance water heater (R-24 insulation)
- electric heat pump water heater
- 0.78-efficient distillate oil water heater
- 0.76-efficient gas water heater (residential only)
- 0.78-efficient gas water heater (commercial only)
- 0.80-efficient gas water heater (residential only)
- 0.82-efficient gas water heater (commercial only)
- 0.85-efficient gas water heater (residential only)
- 0.94-efficient gas water heater

- 0.76-efficient LPG water heater (residential only)
- 0.78-efficient LPG water heater (commercial only)
- 0.80-efficient LPG water heater (residential only)
- 0.82-efficient LPG water heater (commercial only)
- 0.85-efficient LPG water heater (residential only)
- 0.94-efficient LPG water heater
- electric water heater (R-16 insulation) with heat trap
- electric water heater (R-24 insulation) with heat trap
- 0.78-efficient distillate oil water heater with heat trap
- 0.76-efficient gas water heater with heat trap (residential only)
- 0.78-efficient gas water heater with heat trap (commercial only)
- 0.80-efficient gas water heater with heat trap (residential only)
- 0.82-efficient gas water heater with heat trap (commercial only)
- 0.85-efficient gas water heater with heat trap (residential only)
- 0.94-efficient gas water heater with heat trap
- 0.76-efficient LPG water heater with heat trap (residential only)
- 0.78-efficient LPG water heater with heat trap (commercial only)
- 0.80-efficient LPG water heater with heat trap (residential only)
- 0.82-efficient LPG water heater with heat trap (commercial only)
- 0.85-efficient LPG water heater with heat trap (residential only)
- 0.94-efficient LPG water heater with heat trap

Also:

- Insulate existing tank
- Insulate pipe near water heater
- Install low-flow shower heads
- Install faucet aerators
- Decrease service hot water temperature (only possible for certain building types and only done in conjunction with flow reducers)

Loop Systems

Replace existing boiler in central tank circulating system (electric, oil, gas, coal, other fuels) with

- Conventional distillate oil boiler (83, 84, 86.5% combustion efficiencies)
- Conventional residual oil boiler (82, 83.5, 86% combustion efficiencies)
- Conventional gas boiler (80, 81.5, 84% combustion efficiencies)
- Gas pulse condensing boiler (87, 91% combustion efficiencies)
- Conventional LPG boiler (80, 81.5, 84% combustion efficiencies)
- LPG pulse condensing boiler (87, 91% combustion efficiencies)

Also:

- Insulate tank
- Install low-flow shower heads
- Install faucet aerators

Replace existing heat exchanger in central tank circulating system (district steam or district high-temperature hot water) with

- Conventional distillate oil boiler (83, 84, 86.5% combustion efficiencies)
- Conventional residual oil boiler (82, 83.5, 86% combustion efficiencies)
- Conventional gas boiler (80, 81.5, 84% combustion efficiencies)
- Gas pulse condensing boiler (87, 91% combustion efficiencies)
- Conventional LPG boiler (80, 81.5, 84% combustion efficiencies)
- LPG pulse condensing boiler (87, 91% combustion efficiencies)

Also:

- Insulate tank
- Install low-flow shower heads
- Install faucet aerators

E.5 Lighting Retrofit Alternatives

The Pacific Northwest National Laboratory has developed a large database of over 600 lighting technology configurations that are included in FEDS. These lighting technologies are available to be modeled as existing lighting technologies and considered as retrofit technologies. FEDS considers cross-technology substitution only where it is appropriate (e.g., HPS for fluorescent in warehouses). Additionally, FEDS only considers retrofit alternatives that provide at least 90% of the light output of the existing lighting technology configuration.

E.6 Ventilation Retrofit Alternatives

Currently, ventilation system retrofits are not available.

E.7 Miscellaneous Equipment Alternatives

Currently, miscellaneous equipment (plug-load) retrofits are not available.

E.8 Motor Retrofits

FEDS provides the capability to analyze the cost-effectiveness of replacing old, inefficient three-phase asynchronous electric motors with new energy-efficient motors. The list of possible motor retrofits (nearly 1200) were derived from the database of over 18,000 motors contained within the *MotorMaster+* software program developed under the U.S. Department of Energy's Motor Challenge Program. The motors were sorted according to key characteristics (size, speed, voltage, enclosure, etc.) and grouped based on efficiency and cost. For a more detailed (and manufacturer-specific) motor analysis it is suggested that a FEDS run be augmented with *MotorMaster+*.