Title

Final Report on the Energy Edge Impact Evaluation of 28 New, Low-Energy commercial Buildings

Permalink

https://escholarship.org/uc/item/2g50g0bs

Authors

Piette, Mary Ann
Nordman, Bruce
Buen, Odon De

Publication Date

1994-08-01

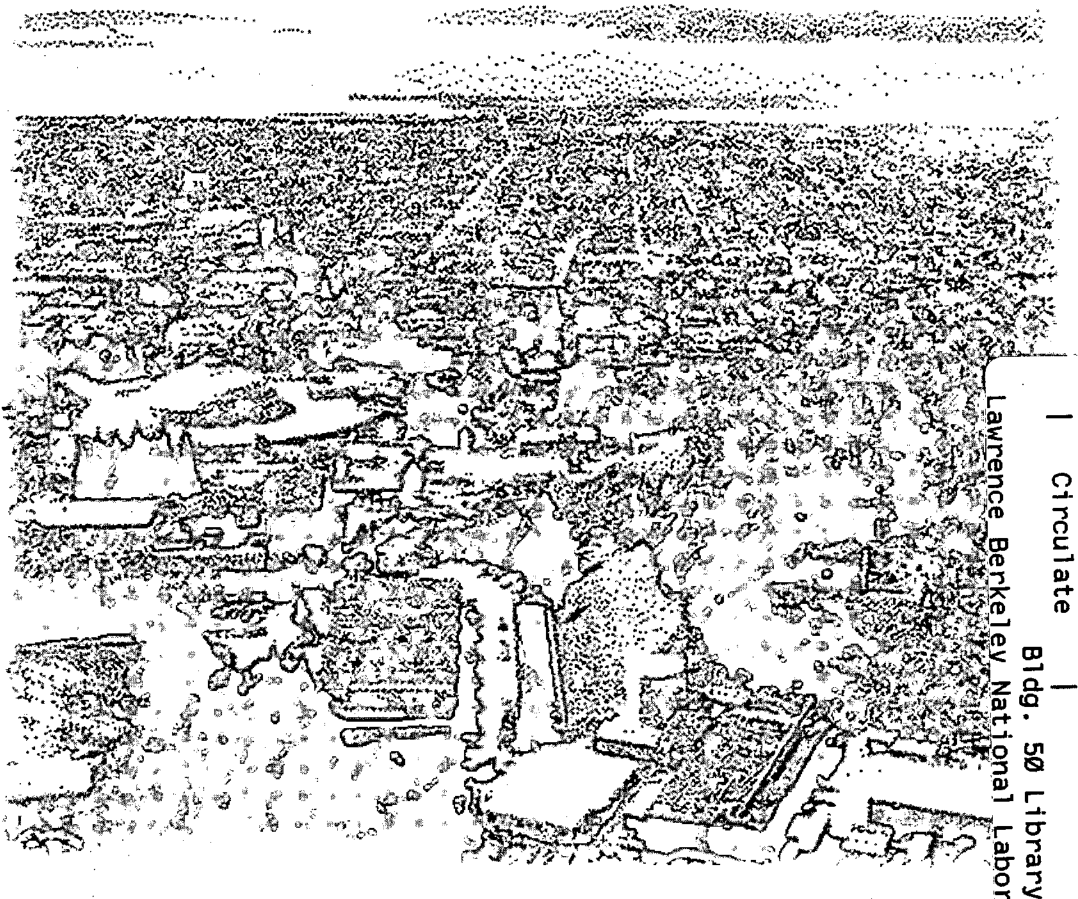
LBL-35154
UC-1600

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Final Report on the Energy Edge Impact Evaluation of 28 New, Low-Energy Commercial Buildings

Mary Ann Piette, Rick Diamond, Bruce Nordman,
Odon de Buen, Jeff Harris, Kristin Heinemeier,
and Katy Janda
Energy and Environment Division

August 1994



LBL-35154
UC-1600

Final Report on the Energy Edge Impact Evaluation of 28 New, Low-Energy Commercial Buildings

Mary Ann Piette, Rick Diamond, Bruce Nordman, Odon de Buen,
Jeff Harris, Kristin Heinemeier, and Katy Janda

Energy & Environment Division
Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

August 1994

This work was supported by the Bonneville Power Administration and the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Table of Contents

Appendix A

These appendices contain additional detail on the evaluation analysis by chapters corresponding to the main report. Appendix A1 provides supporting documentation on Chapter 1, Appendix A2 provides supporting documentation on Chapter 2, etc.

Appendix B

These appendices contain summaries of all program data for each building arranged alphabetically by building.

Acknowledgements

We would like to acknowledge the contributions of the individuals named below. In particular, we would like to thank Bruce Cody, Michael Kaplan and Grant Vincent for their ongoing assistance in completing this research project. While many other individuals have also contributed significantly to the information and analysis presented in this report, we wish to give special thanks to:

Ken Anderson, Pacific Power & Light
Steve Baker, Oregon Department of Energy
Mary Beecroft, Pacific Northwest Laboratory
Nancy Benner, Portland Energy Conservation, Inc.
Roger Bennett, Bonneville Power Administration
George Caan, Washington State Energy Office
Bruce Cody, Bonneville Power Administration
Bill Gilbertson, William Gilbertson, Inc.
Alan Grill, Bonneville Power Administration
Mark Halverson, Pacific Northwest Laboratory
Jeff Harris, Northwest Power Planning Council
Tudi Haasl, Portland Energy Conservation, Inc.
Judith Heerwagen, University of Washington
Gary Insley, Bonneville Power Administration
Ed Julkowski, Pacific Northwest Laboratory
Mike Kaplan, Kaplan Engineering
Doug Kilpatrick, Washington State Energy Office
Bill Koran, Portland Energy Conservation, Inc.
Les Lambert, Lambert Engineering
Peggy Leanderson, Pacific Northwest Laboratory
Susan LeMaster, Portland Energy Conservation, Inc.
Bob Lucas, Pacific Northwest Laboratory
Will Miller, Portland Energy Conservation, Inc.
John Perry, Oregon Department of Energy
Fran Petersen, Bonneville Power Administration
Rob Pratt, Pacific Northwest Laboratory
William Sandusky, Pacific Northwest Laboratory
Ralph Shoemaker, Bonneville Power Administration
Tim Steele, Bonneville Power Administration
Tim Storey, TBS Associates
Tony Usibelli, Washington State Energy Office
Grant Vincent, Bonneville Power Administration
Kalim Winata, Pacific Power & Light
Rachel Yoder, Pacific Power & Light

Preface

This report presents the findings of the Energy Edge Impact Evaluation. It is the fourth and final report in a series of project impact evaluation reports[1]. Energy Edge is a research-oriented demonstration of energy efficiency in 28 new commercial buildings. Beginning in 1985, the project, sponsored by the Bonneville Power Administration (BPA), was developed to evaluate the potential for electricity conservation in new commercial buildings. By focusing on the construction of new commercial buildings, Energy Edge meets the region's goal of capturing otherwise lost opportunities to accomplish energy conservation. That is, the best time to add an energy-efficiency measure to a building is during the construction phase.

The project provides new insights on several aspects of commercial building performance, including construction, operation, and evaluation methods. Questions we investigated include: How do the actual energy use and costs compare to the predicted values (both for the building total and by end use)? How do these buildings compare to other new buildings in the region? How do these buildings change over time? We addressed these questions by examining utility billing data for the buildings (in some cases up to five years of records), hourly sub-metered end-use data, and output from calibrated simulation models.

Objectives of the Energy Edge Project

The Energy Edge project was based on designing and assessing new commercial buildings to reduce energy consumption by 30 percent below a hypothetical baseline building. The baseline energy use was determined by applying the 1985 Model Conservation Standards (MCS) for energy performance (similar to ASHRAE 90A-1980, with more stringent requirements for lighting) to each building. The MCS applied only to electricity use, although some of the Energy Edge buildings use fossil fuels for non-MCS end uses (e.g., back-up heating, service hot water, and cooking appliances).

The Impact Evaluation has had three primary objectives. The first objective was to develop and refine the methodology for monitoring and data analysis, both to help direct the research efforts to evaluate Energy Edge and to provide guidance on data collection and analysis in future demonstrations or conservation resource-acquisition programs. This objective was met with LBL's participation in project planning activities.

The second objective was to use monitored data, calibrated ("tuned") building models, and other information to assess:

- *Overall performance* of Energy Edge buildings and incremental costs and savings, by measure, in comparison to buildings conforming to the Model Conservation Standards (MCS),
- *Factors contributing* to energy performance, cost-effectiveness, and occupant satisfaction,
- *Net impact* of the Energy Edge project, compared with regional trends and other programs, and
- *Design-phase predictions* compared to actual building performance and cost-effectiveness, to improve prediction methods and assumptions.

This report reviews the findings on these subjects.

The third objective was to provide timely and relevant information to BPA, the Northwest Power Planning Council, and others on the performance and cost-effectiveness of Energy Edge buildings and measures, the impact of the project, and implications for future building design, commercial sector programs, and acquisition of conservation resources. The ongoing series of reports and technical memorandums from LBL provided this feedback to BPA and the Power Council.

---

[1] The first three evaluation reports are:

Energy Edge Impact Evaluation: Findings and Recommendations from the Phase One Evaluation, Harris, J., Diamond, R., de Buen, O., Hatcher, A., Nordman, B., and Piette., M.A. Prepared for BPA, LBL-30358, May, 1990.

Energy Edge Impact Evaluation: Early Overview, Diamond, R.C., Harris, J.P., Piette, M.A., de Buen, O. and Nordman, B., Prepared for BPA, LBL-30711, December, 1990.

Energy Edge Impact Evaluation: Middle Overview, Diamond R.C., Piette, M.A., Nordman B., de Buen O., and Harris J.P., Prepared for BPA, LBL-32764, May, 1992.

Perspectives

Our perspective in the evaluation incorporates a broad interpretation of building energy performance. The energy *performance* of a building is not the same as its energy *use*; performance indicates a relationship between energy used and services (comfort, convenience, amenity) provided to occupants. Similarly, the *overall* performance, or success, of a building includes energy as only one component. While BPA and others are primarily interested in the energy performance of Energy Edge versus conventional (MCS) buildings, the results must be interpreted in light of other dimensions of success that are important to owners and occupants, including cost-effectiveness, marketability, comfort, aesthetics, reliability, etc. The market will not readily accept "0.7 MCS" levels of energy performance without assurance that the building is otherwise attractive, functional, and marketable. Conversely, features that may be marginal from an energy perspective alone may be very popular for other reasons. Although Energy Edge focuses on decisions at the design stage, energy performance, and other aspects of overall building success depends on more than design. The energy performance and cost-effectiveness of many design features also depend on the quality of construction, building commissioning, and long-term operating practices.

We have developed a series of estimates of the *net* effects of Energy Edge to quantify the energy savings and cost-effectiveness of the complete project. Arriving at the estimates is complicated by the lack of an explicit control-group and extensive, but incomplete data from the sample of 28 buildings. Eighteen of the buildings were evaluated with calibrated simulation models. We present building-by-building comparisons with conventional design to establish the context for Energy Edge and examine underlying trends in new commercial construction and energy-related code enforcement.

One reason for conducting the evaluation was to be able to use experience with Energy Edge as a guide to future decisions about improving energy performance in new buildings. Thus, assessments of program successes and mistakes are most useful if they have some bearing on what to do (or not do) in future projects and programs. The project, for example, demonstrated the need for commissioning and spawned the development of commissioning guidelines tested on one of the Energy Edge buildings.

Executive Summary

The Energy Edge project provides conservation planners with information about how energy-efficiency measures perform in actual, occupied commercial buildings. The goal of Energy Edge was to redesign new commercial buildings to achieve energy consumption 30 percent below a hypothetical baseline. Baseline energy use was generally determined by simulating a basecase building that met the Model Conservation Standards (MCS). The primary objective of the impact evaluation was to assess the overall performance of the Energy Edge buildings and examine the energy savings and cost-effectiveness of individual energy-efficiency measures. Over 200 individual energy-efficiency measures were tracked. This report summarizes the performance data for all 28 buildings and results from 18 buildings that were evaluated using post-occupancy Tuned simulation models. Three key findings are as follows:

- **Commissioning and improved operations and maintenance (O&M) are needed to ensure delivery of energy savings.** A primary reason the energy-efficiency measures did not save as much energy as assumed during the design stage was poor commissioning and O&M. Improved performance measurement techniques are needed to identify and correct ongoing operational problems using enhanced data management and visualization tools.
- **Reducing building energy use by 30% beyond code is a feasible target, but difficult to achieve.** Most of the Energy Edge buildings consumed significantly less energy than comparable new buildings, though not achieving the 30% savings target. The greatest savings were found in the small office buildings, which used about 40% less energy than comparison buildings without compromising building quality or occupant satisfaction.
- **Lower-cost analysis techniques are needed, with special attention to developing better information on common building practice in new construction.** The accuracy of the evaluation, based on expensive and time consuming monitoring and modeling, was hampered by difficulties in defining baseline conditions.

Key findings listed below are organized by subject corresponding to five chapters: program evaluation, building performance, measure performance, ensuring optimal performance of measures, and methodology assessment. The recommendations that follow from the findings are oriented toward improving future demand-side management programs, evaluations, and research and demonstration efforts.

1. Program Evaluation

Findings

Total annual energy savings were predicted to be about 17 GWh for all 28 buildings. Estimates of the achieved savings range from 13 to 71 percent of predicted savings. The range in estimates of achieved savings is based on the different methods used to extrapolate from incomplete results for some of the buildings to total savings for all 28 buildings. The lower savings estimates are dominated by the poor performance of the largest buildings. Several of the smaller buildings saved more than predicted and consumed less energy than predicted.

The main reason for the reduced savings is the change in the actual building systems and energy-efficiency measures. A second reason is that many measures, especially control measures, did not operate as well as predicted because of poor commissioning and ongoing operations and maintenance (O&M) problems. Average energy use was about 40% greater than predicted, with the greatest increase from heating, ventilation, and air-conditioning (HVAC) equipment. Longer hours of operation and poor O&M conditions are the likely cause for the increase.

Only one of the buildings met the program objective of reducing energy use by 30% below the code baseline, while meeting the cost-effectiveness criterion target of 5.6 ¢/kWh However, in reviewing the Design-phase estimates of measure cost-effectiveness, one-third of the buildings did not meet the target when they entered the program.

Recommendations

Energy-efficiency and Demand-Side Management (DSM) programs need to ensure that careful tracking and archiving of building and measure characteristics is conducted to evaluate how installed systems compare with design specifications. Changes in building operating conditions should also be carefully tracked, with special attention to typical HVAC operating conditions. Perhaps the most significant opportunity to reduce energy use in actual buildings is to turn off devices (e.g. fans, pumps, heat, or lights) when they are not needed. Analysis of hourly whole-building data from in-place utility meters or energy management and control systems should be exploited to identify and correct off-hour energy waste.

2. Building Performance

Findings

Most of the Energy Edge buildings consumed significantly less energy than comparable new buildings. The Energy Edge small office buildings (which consume about 12 kWh/ft^2-year) have lower energy use than similar new buildings, with savings between 30 and 50%. The lighting and shell characteristics reflect energy-efficient design principles, and are significantly different than common practice, which partly explains their low energy use.

On average, energy use for all 28 buildings increased during the first four years of operation, though the rate of growth slowed each year. Fourth year energy use was six percent greater than third year, and almost 40% greater than predicted.

Recommendations

Evaluations of the energy performance of new commercial buildings should include comparisons with regional stock data, including an examination of code compliance issues. Building characteristics data should be combined with energy-use data to identify the impact of DSM or other energy-efficiency programs on improving overall building energy efficiency. Evaluations of new commercial construction cannot rely on first or second year energy use data to be representative of long term trends. Further research on persistence of savings is needed to evaluate how the measures perform over time.

3. Measure Performance

Findings

On average, post-occupancy Tuned energy savings for individual measures were slightly greater than half of Design-phase predicted energy savings. Among the 78 measures evaluated in the 18 Tuned building models, 41% met the cost-effectiveness criterion (cost-of-conserved energy [CCE] under 5.6 ¢/kWh). Among the general classes of measures, the refrigeration and miscellaneous measures were the most cost-effective with median CCEs of 5.4 and 1.6 ¢/kWh, respectively. Lighting measures were the next most cost-effective at 7.5 ¢/kWh (median), followed by shell measures at 7.8 ¢/kWh. The HVAC measures were the least cost-effective, with a median CCE of 12.7 ¢/kWh.

The most important reason energy savings were not as great as predicted is that measures changed. For example, the installed insulation levels were often less than the design values, and lighting power densities higher than initially specified. A second important reason for lower savings was the problems associated with dynamic measures, such as control measures. These measures were often poorly commissioned, that is, they were not correctly set-up for proper control, calibration, and operation. Analysis of specific measures, such as energy-efficient heat pumps and economizers, revealed that the energy savings from ensuring proper operation and control of building equipment can save as much, or more energy than installing more efficient equipment.

Recommendations

Careful tracking of measure characteristics is needed to ensure that the energy-efficiency measures installed in a building are the same as those specified in the design. Or, if a measure changed, the post-occupancy performance evaluation methodology should be able to account for the change. Verifying that installed equipment operate correctly is crucial to ensure energy savings. These factors should be considered when evaluating the cost-effectiveness of an energy-efficiency measure.

4. Ensuring Optimal Performance of Measures

Findings

Commissioning of energy-efficiency measures during building start-up is crucial to ensure that energy savings are achieved. Over two-thirds of the problems with measures in the Energy Edge buildings would likely have been caught and corrected with proper commissioning. Energy savings from the pilot commissioning study at the Director building resulted in reducing energy use by 8%. Further opportunities for another 4% in energy savings were identified.

Recommendations

Commissioning procedures are needed to ensure optimal performance of energy-efficiency measures and whole-building systems. These procedures include verifying proper equipment installation and calibration, functional and diagnostic testing, and preparation of O&M guidelines supported by O&M training. Further compilation and analysis of commissioning case studies is needed to evaluate the costs and benefits of commissioning. Careful tracking of deficiences corrected by commissioning is needed to identify how to reduce the need for this extra step in building start-up, or retrofit start-up.

5. Methodology Assessment

Findings

Although it took about 400 hours to develop each Tuned model, develop the baseline model, and evaluate the energy performance of each measure, the energy savings and cost estimates are uncertain for some energy-efficiency measures because of difficulties in defining baseline assumptions that reflect the building code and current practice. Measures that were most difficult to model are HVAC and lighting controls, and infiltration measures. Furthermore, shortcomings in the project documentation hampered comparisons of building characteristics, measure definitions, costs, and O&M problems. Continuous end-use monitoring was expensive and often did not provide suitable information for the analysis of measure performance. Direct tests, combined with functional and diagnostic testing for commissioning, could have been useful to determine the impact for many measures.

Recommendations

Future program evaluations should consider lower-cost, simplified methods for developing post-occupancy estimates of the performance of energy-efficiency measures using short-term monitoring, building characteristics, hourly whole-building energy use, and information from energy management and control systems. In many cases a direct test, rather than continuous end-use monitoring, is best (or only) way to determine a measure's impact. These tests should be combined with functional and diagnostic testing for commissioning during building start-up. Ongoing annual check-ups revisiting the energy-efficiency measures, building conditions, and control sequences would help maintain energy savings over time. Increased standardization in modeling guidelines and data reporting formats would greatly increase the ability of evaluators to track changes in building and measure characteristics. Further analysis of common practice regarding HVAC control sequences is needed to improve modeling of these systems.

Report Organization

This report is divided into five main chapters with additional details in two appendices. Prior to the first chapter is a glossary that describes several specific terms used in the Energy Edge evaluation.

The first chapter (Project Evaluation) includes a description of the Energy Edge project and the overall results from the analysis. We review the *Tuned Model* evaluation methodology and a second evaluation methodology based on comparisons of the Energy Edge buildings with regional building stock data. This chapter also presents estimates of the total energy savings for all 28 buildings in the project. Design-phase energy savings predictions are compared against the Tuned model savings. Total costs for the Energy Edge project are presented, including an estimate of the project's cost effectiveness.

Chapter 2 (Building Performance) begins with a comparison of actual energy use from long-term utility billing histories with Design-phase predictions of energy use. The second section examines end-use data trends. Section 2.3 presents a detailed look at the performance of the seven small office buildings for which we have the most complete set of information, comparing them with other regional data on new office buildings. Section 2.4 presents a less detailed comparisons for the other Energy Edge building types. The final section in Chapter 2 summarizes results from surveys of occupant satisfaction.

The third chapter (Measure Performance) discusses the energy savings and cost effectiveness of individual energy-efficiency measures, summarizing results for 219 individual measures. The chapter begins with a discussion of the measure cost data. The second section is a discussion of the energy savings and cost effectiveness results of individual measures from the 18 Tuned models. Section 3.3 summarizes results from previous analyses of individual measures, focusing on three measure types: heat pumps, economizers, and occupancy sensors.

Chapter 4 (Ensuring Optimal Performance of Measures) provides an overview of the problems found in the Energy Edge buildings. We describe design, installation, product performance, and operations and maintenance problems with 42 measures. The information from this analysis came from anecdotal comments in the operations and maintenance audits. This chapter also includes a description of the results from the Director Building pilot commissioning study.

The fifth chapter (Methodology Assessment) discusses the strengths and weaknesses of the evaluation methodology. It begins begin with a review of the tuning methodologies and discusses results from one building to illustrate the type of data available from each of the tuned models. Section 5.3 reviews the strengths and weaknesses of the Tuned model evaluation approach and Section 5.4 reviews differences between the Design-phase and Tuned models. The fifth section in Chapter 5 summarizes evaluation activities beyond the Tuned model effort and discusses shortcomings of the analysis from a broad research perspective. This is followed by a section on suggestions for future program evaluation methodologies. The final section compares the performance of the measures from the Energy Edge Tuned models with the energy savings assumed in the Energy Smart Design Prescriptive Path for small buildings, which is widely used throughout the Northwest.

Chapter 6 is a bibliography.

Two appendices accompany the main report. Appendix A contains additional details on the evaluation organized by chapters corresponding to the main report (e.g., Appendix A1 provides supporting documentation on Chapter 1, Appendix A2 supports Chapter 2, etc.) Appendix B contains building by building summaries of all program data arranged alphabetically by building.

Glossary

Throughout this report we use terms that are uniquely defined within the project context. The following is a summary of these terms.

Base - *Base* is the specific hypothetical baseline building defined for each Energy Edge building. Design-phase and Tuned baselines were developed.

BPA-funded and **owner-funded** - BPA paid for the incremental cost of the energy-efficiency measures, which are *BPA-funded.* Some efficiency measures were identified during the design process that BPA did not fund, but the owners chose to implement out of their own pocket; these are *owner-funded* measures. Both types of measures were tracked in the analysis.

Costs - Three kinds of cost data were developed: predicted, reported, and standard, as described below. The difference between the costs for the Base and Edge building systems is the *incremental* cost for the energy savings feature. Unless otherwise noted, all costs presented in this report are incremental costs. We report nominal costs, and cost per unit floor area. The costs reported are in 1991 dollars unless otherwise noted.

Predicted Costs - During the Design-phase activities a set of *predicted* measure costs were developed.

Reported Costs - As the buildings were constructed, and incentive payments made, *reported* costs were recorded for 16 buildings.

Standard Costs - *Standard* costs were developed to reduce the variation in methods used to develop the predicted and reported costs. These are measure costs for the Seattle area in 1991 dollars.

Design-phase - Computer simulations were performed during the building design stage to estimate the energy savings for energy-efficiency measures. These simulations included estimating energy end-uses (lighting, heating, cooling, etc.) for the Base and Edge building.

Edge - *Edge* is the Energy Edge building itself, in its Design-phase, Tuned, or actual form.

Model Conservation Standards (MCS) - This regional building energy code served as the baseline against which the Energy Edge measures were evaluated (NWPPC, 1985). The MCS are similar to ASHRAE Standard 90A-1980 with more stringent requirements for lighting (ASHRAE, 1980).

Measures - An energy-efficiency *measure* is a specific change between the Base and Edge buildings that results in energy savings (though some measures failed and had zero or negative tuned savings). Some measures appear only in the design-phase or only in the tuned buildings. We also defined over 40 measure "aggregations" to account for the fact that data were often recorded in combination. For example, in 12 buildings, wall and roof insulation combination measures are tracked because the energy savings or cost data from the Design-phase predictions were combined.

Tuned - 18 of the Energy Edge buildings had "Tuned" simulation models. These model were calibrated with monitored end-use data and developed to match actual building performance. After the Edge building was tuned, a Tuned Base building was derived. Tuned measure energy savings were calculated (both interactive and parametric) as the difference between these two.

Acronyms

BPA	Bonneville Power Administration
BTU	British Thermal Unit (3413 Btu = 1 kWh)
CCE	Cost of Conserved Energy (¢/kWh)
CDD	Cooling Degree Days
CFL	Compact Fluorescent Lamp
COP	Coefficient of Performance
CRR	Capital Recovery Rate
DHW	Domestic Hot Water
DPT	Daily Profile Tuning (done in pilot before MCT)

DSM	Demand-Side Management
ECM	Energy-Conservation Measure
EMCS	Energy Management and Control System
ESD	Energy Smart Design Program
ETP	Equivalent Thermal Parameters
EUI	Energy-Use Intensity (kWh/ft^{2}year)
GWh	Gigawatt Hours (10^9 Wh, or 10^6 MWh)
HDD	Heating Degree Days
HVAC	Heating, Ventilation, and Air-Conditioning
LBL	Lawrence Berkeley Laboratory
LPD	Lighting Power Density
MCS	Model Conservation Standards
MCT	Monthly Consumption Tuning
MWh	One thousand kWh
NWPPC	Northwest Power Planning Council
O&M	Operations and Maintenance
PNL	Pacific Northwest Laboratory
PECI	Portland Energy Conservation Inc.
STEM	Short-term Energy Monitoring
TMY	Typical Meteorological Year
UA	Thermal insulation value (Btu-ft^2/hour°F)
VAV	Variable-Air-Volume HVAC System
VVT	Variable-Volume Variable-Temperature HVAC System

Chapter 1. Program Evaluation

Key Findings in this Chapter

- Total energy savings were predicted to be about 17 GWh for all 28 buildings. Estimates of total actual achieved savings (for all buildings) range from 13 to 71 percent of predicted savings, depending on how the data are extrapolated from incomplete performance results. The lower savings estimates are dominated by the poor performance of the largest buildings. Several of the smaller buildings saved more than predicted and consumed less energy than predicted.
- The main reason for the reduced savings was the changes in the actual building systems and energy-efficiency measures from the Design-phase predictions. A second reason is that the many measures, especially control measures, did not operate as well as predicted because of poor commissioning and ongoing operations and maintenance (O&M) problems.
- Average energy use was about 40% greater than predicted, with the greatest increase from heating, ventilation, and air-conditioning (HVAC) equipment. More hours of operation and poor O&M conditions are the most likely cause for the increase.
- Only one of the buildings met the program objective of reducing energy use by 30% beyond the baseline code, while meeting the cost effectiveness criteria of 5.6 ¢/kWh. However, in reviewing the Design-phase predictions of measure cost effectiveness, one-third of the buildings did not meet the target as designed.

1.0 Introduction

Background

Energy Edge was a research-oriented demonstration project developed by the Bonneville Power Administration (BPA) to evaluate the cost-effectiveness of designing and constructing buildings that exceed the energy-efficiency requirements of the 1985 Model Conservation Standards (MCS) (NWPPC, 1985). The project was unique as perhaps the most detailed evaluation of energy-efficiency in new commercial buildings ever conducted. This report provides a summary of the key findings from the assessment of the energy performance of 28 buildings.

Measuring the energy savings from a particular energy-efficiency measure in a new commercial building is not a trivial task. Unlike with an existing building, there is no "before" case from which to evaluate energy savings. Comparing energy use from a building with the *Design-phase* predicted savings is complicated by differences in as-built building systems, occupancy patterns, and modeling biases[1]. We can only guess how a basecase building might be different from the one built with the efficiency measures included. Thus, the Energy Edge project was designed to collect a tremendous amount of information about the building design and performance histories from the Design-phase models to the end-use metering and post-occupancy *Tuned* models.

The science and art of evaluating new commercial buildings are not well developed. A recent paper on measurement of energy savings commented that, "... if evaluation methodologies for commercial retrofit programs seem to be in their infancy, methods for new construction programs must be in-utero at this time (Fels and Keating, 1993)." Looking back at the project in retrospect we comment (in Chapter 5) on how the data collection and evaluation activities could have been improved. However, even after the eight years of the project's history we cannot identify a single best method to assess energy-efficiency measures in new commercial buildings. Rather, a multitude of evaluation approaches are needed to ensure that the biases of a particular technique does not mislead the conclusions.

Participants in the Energy Edge project have produced several dozen conference papers and reports on the buildings and the project. Individual reports on the post-occupancy simulation models were developed for 18 of the buildings[2]. Miller et al., (1990) summarizes lessons learned from a project

---

[1] The terms *Design-phase* and *Tuned* are further explained below and in the glossary. Tuned models were generated using the Monthly Consumption Tuning methodology discussed in Chapter 5.

[2] Reports on the Tuned simulation models complete for 18 of the 28 buildings are available from the Electric Ideas Clearinghouse operated by the Washington State Energy Office.

sponsor's perspective. We reference many of the papers and reports that discuss Energy Edge in the following chapters, with full citations in the Chapter 7 (Bibliography).

Chapter Overview

This chapter includes a description of the Energy Edge project and the overall results from the analysis. We provide a brief review of the *Tuned Model* evaluation methodology that involves calibrating computer simulation models with metered end-use data, then using the models to estimate energy savings for each energy-efficiency measure. A second evaluation methodology is described called the *Comparison Buildings* approach, offered to provide a broader context for the results from the Tuned models.

Following the description of the methodology we present results from the analysis of the energy-efficiency measures evaluated in 18 Tuned Models and discuss the performance of all 28 buildings. Ten of the 28 buildings were not modeled after occupancy began; only Design-phase predictions of measure performance are available for them. We contrast results from the Design-phase simulations with results from the Tuned models.

The final two sections present estimates of the total, net energy savings for all 28 buildings in the project. Design-phase energy savings predictions are compared against the Tuned model savings. Another approach derives net savings using energy data from utility bills for all 28 buildings with regional comparison buildings data. We also compare the energy data from utility bills with the Design-phase *Base* energy use, which would have been the baseline for comparison if the Tuned models were not developed. Total costs for the project are presented, including an estimate of the project cost effectiveness.

1.1 Project Description

The $14.6 million Energy Edge program began with a design competition to identify buildings undergoing initial construction or extensive remodeling. Later in this chapter we review the elements of the total program costs and compare the costs with the energy savings.

Potential building designs had to use electric heat to be eligible. Computer simulations were developed for each building that entered the competition. The aim of the Design-phase simulations was to evaluate the cost effectiveness of energy saving features that might reduce energy use by 30% beyond baseline building that meets the MCS and has no special energy-efficiency measures. The 30% savings target was measured against the MCS code end uses only, which include lighting, heating, cooling, ventilation, exterior lights, and water heating. MCS code does not include other loads such as miscellaneous plug loads (e.g. office equipment), refrigeration, or cooking, although these latter two loads have been considered in the evaluation of the restaurants and grocery stores.

Four Energy Edge sponsors marketed the competition to building owners, architects, developers, and others in the building industry. The four sponsors were: the Oregon Department of Energy, the Washington State Energy Office, Portland Energy Conservation Incorporated, and Pacific Power and Light.

After selecting the buildings, BPA paid for the incremental cost of the energy-saving features. The cost for the total package of measures had to be below 45 mills/kWh saved (4.5 ¢/kWh in 1986 dollars, 5.6 ¢/kWh in 1991 dollars) and reduce energy use by 30% compared to the MCS baseline. In our review of the Design-phase energy savings and cost data we found that many of the packages of energy-efficiency measures did not meet this criteria, as discussed later in this chapter. Many building owners installed additional measures identified in the design studies. These measures are referred to in this study as "owner-funded" measures. The measures that were actually installed in the buildings often differ from those considered in the Design-phase, which complicates the evaluation.

Buildings selected for the project range in size and type. They range from the second largest building in Seattle (Gateway Tower) to several fast-food restaurants (including a Burger King and a McDonald's). The buildings were constructed and occupied between 1986 and 1989. Two major renovation projects were included (Montgomery Park and Director).

Detailed monitoring plans were developed and data acquisition systems installed to collect information about how energy is used in each building. On-site weather data were collected for use in model calibration. Lambert Engineering designed, installed, and operated the data collection systems (Gardner and Lambert, 1987).

1.2 Evaluation Methodology

Tuned Model Approach

The Tuned model evaluation methodology was developed to provide a detailed analysis of each efficiency measure based on actual building operating conditions. After the buildings were close to full occupancy, information from the operation and maintenance audits plus hourly end-use and on-site weather monitored data were used to develop computer simulation models to represent the actual building. Buildings were modeled with the DOE-2.1 simulation model (versions C, D, and E). Most of the modeling was done by or supervised by one organization, Kaplan Engineering.

A Tuned Base model is derived by defining code baseline conditions for each BPA-funded and owner-funded measure in the Tuned model. Each measure is individually modeled against the Tuned Base, and a levelized cost is calculated. BPA-funded measures are also modeled as a complete, interactive package.

BPA's levelized cost formula is equivalent to a cost of conserved energy (CCE) based on a 3% discount rate, as further described in Chapter 3. The CCE can be described as:

$$CCE = \frac{\text{initial investment} \times \text{capital recovery rate}}{\text{annual energy saved}}$$

The capital recovery rate (CRR) annualizes the investment. In terms of the real annual discount rate d and measure lifetime n (years), the CRR is given by the expression:

$$CRR = \frac{d}{1-(1+d)^{-n}}$$

Measure lifetimes are based on BPA's technical requirements for the Energy Smart Design program.

The CCE allows easy comparison with both the electricity rates customers pay, and with the cost characteristics of utility supply sources, which are usually expressed in levelized cost per kWh rather than payback periods. These initial investment costs are incremental construction costs only: labor, materials, and overhead. Measure costs do not include measure design costs, program delivery, or operations and maintenance costs, though some of these costs were tracked, as discussed in Chapter 3.

Although the levelized costs were calculated in each Tuned model, we have re-calculated CCEs for each measure for the following reasons. First, LBL CCEs have been corrected to ensure that all the costs are inflated to 1991 dollars. Second, we have made a few corrections to the cost data when errors were evident. For example, we corrected the roof insulation costs at the Evergreen building because of an error in the area used to estimate the cost of the insulation. Third, some of the Tuned models contained errors in the way aggregate costs and energy savings measures were calculated when a measure with negative energy savings was included in the package. These were corrected. And finally, there were many cases where two measures were treated as one in the Design-phase predictions, making it difficult to compare the results with the Tuned model. Our recalculations allowed us to compare groups of measures with the Design-phase predictions. All measure costs and lifetimes are listed in Appendix B.

Energy savings and cost-effectiveness of the interactive package of measures for the 18 Tuned models are presented later in this Chapter. Further details on the model tuning and levelized cost analysis are contained in the Appendix A1. See the following reports for additional information on the model tuning methodology: Kaplan Engineering, 1989, Kaplan et al., Aug. 1990, and Kaplan Engineering and PECI, 1992. Energy savings estimates for each efficiency measure are discussed in Chapter 3, and Chapter 5 provides an example of the results from one of the Tuned models (in Appendix B for each building).

Comparison Buildings Approach

The Tuned model methodology was designed to be as objective as possible in defining a hypothetical MCS Base building for comparison with the actual Energy Edge building. Unfortunately, defining baseline conditions is difficult, especially for end-uses not regulated by code, such as refrigeration, cooking, or kitchen lighting. Defining baseline characteristics is also complicated by compliance options within codes. Moreover, codes contain minimal coverage of control systems, with few, if any, requirements on how to actually operate controls.

The challenge in defining the appropriate baseline moves beyond code compliance and asks: "What would have been built without Energy Edge?" and "What is common practice?" Ideally, the comparison buildings approach would have included developing a statistically valid sample of non-participants to serve as a baseline for the Energy Edge buildings. Without such a sample we drew upon existing sets of buildings data to make the comparisons. We compared energy use and characteristics of both the Energy Edge and the hypothetical Base buildings against other new commercial construction in the Pacific Northwest. We have used a variety of published data to estimate typical energy use intensities for each building type. The major drawback of this simple approach of comparing whole-building energy use is that it does not consider conditions in the building that create more intensive than a typical building, such as more hours of operation or process loads such as a computer center, or a severe climate.

Following the discussion of the Tuned models we present an estimate of total energy savings for all 28 buildings based on comparing the energy use from utility bills with the regional comparison buildings. Comparison buildings data are further discussed in Chapter 2.

1.3 Performance of the Energy Edge Buildings

Table 1.1 lists the name, location, size, predicted savings, actual energy use (from utility bills) and change in energy use from predicted for all 28 buildings. In general, the predicted savings percentage does not include the plug loads, which is a non-MCS end-use. However, the savings percentages for restaurants, grocery stores, and Waves Motel include all end-uses because some of the energy-efficiency measure affected non-MCS code end-uses such as cooking[3]. Post-occupancy Tuned simulation models were developed for 18 Energy Edge buildings, and ten buildings were dropped because of lack of funds. Compared to the total energy use estimated during the design phase, energy use in the actual buildings is, on average, about 40% greater than predicted, as listed in Table 1.1.

The energy use of the buildings ranges from 32% (the STS building) less than Design-phase predicted to 148% greater (Eastgate), with a median increase of 27%. Actual energy use for one-fourth of the buildings were within 10% of the Design-phase prediction. As discussed later in Chapter 5, the greatest increase in energy use is from heating, ventilation, and air-conditioning (HVAC) equipment. More hours of operation and less use of night set-back are probably the most common cause for the increase.

Performance of Packages of Measures

Energy savings from the Tuned models were less than the design-phase predicted savings at most of the buildings and for most of the measures. The lack of savings was not only related to the performance of the efficiency measures, but was also a result of changes in the buildings from the predictions and difficulties in modeling some measures.

Average predicted energy savings for the 18 Tuned buildings was 33% of the Design-phase Base energy use. Post-occupancy Tuned savings estimates were less, with average savings of 17% of the new baseline (Tuned Base) energy use. Results for each building are shown in Table 1.1. For most buildings, the savings fractions are based on the MCS end-use totals only, which do not include plug loads. However, we include two non-MCS end-uses, cooking and refrigeration, in the savings fraction for the fast-food restaurants and groceries because the energy-efficiency measures primarily affect these end-uses. The percentage savings include both BPA- and owner-funded measures.

Results from the Tuned models show that the cost of conserved energy for the interactive package of measures funded by BPA ranges from 1.5 ¢/kWh (Thriftway) to one case where there were no net savings for the package of measures (Bellevue). Based on the LBL results, six of the 18 buildings met the cost-effectiveness criterion of 56 mills/kWh for the total package of measures, and a seventh (Marsing) is within 5% of the target. Only one of these buildings met the 30% savings target (Marsing). The most cost-effective measure packages were in the two groceries and the fast-food restaurant, all of which involve non-MCS end uses.

---

[3] For example, McDonald's was predicted to save 42% of the MCS end-uses, but only 15% of whole-building energy use. A few of the savings estimates are less than 30% because of inconsistencies in energy data tracking during the early program design (Montgomery) and changes in building boundaries (Evergreen).

Table 1.1. Energy Use, Measure Savings and Cost-Effectiveness of the 28 Energy Edge Buildings.

Building	Location	Floor Area (*kft^2*)	CCE (*$91*)[a] Tuned	LBL (*¢/kWh*)	% Savings[b] Pred.	Tuned	EUI (*kWh/ ft^2year*)[c]	% Change in EUI from Pred.
Small Office								
Caddis McFaddin	Spokane, WA	2.1	—	—	39	—	10	9
Siskiyou	Ashland, OR	3.0	28.7	31.0	42	29	8	-7
Hollywood	Portland, OR	3.1	23.5	30.7	42	8	11	33
STS	Ellensburg, WA	4.3	67.4	67.8	39	15	10	-32
East Idaho Cred. Union	Idaho Falls, ID	5.3	17.4	23.6	35	15	13	52
Dubal Beck	Portland, OR	8.5	7.3	11.2	28	23	13	32
Landmark	Yakima, WA	13.4	14.0	10.4	34	18	14	5
West Yakima	Yakima, WA	16.2	—	—	33	11	11	48
Large Office								
Emerald PUD HQ	Eugene, OR	24.8	15.5	9.9	37	29	10	36
Eastgate	Bellevue, WA	25.1	4.3	5.3	40	26	21	148
Director	Portland, OR	79.7	8.0	12.0	37	25	12	16
Eugene W&P Board	Eugene, OR	91.3	—	—	28	—	20	-22
Bellevue Place	Bellevue, WA	389.0	na	na	31	-6	22	5
Montgomery Park	Portland, OR	782.9	—	—	22	—	16	104
Gateway Towers	Seattle, WA	1,087.0	—	—	46	—	25	25
Retail								
Evergreen	Tacoma, WA	21.1	11.4	2.9	20	5	22	43
Fast-Food								
Skipper's	Bellevue, WA	2.5	—	—	50	—	61	71
Burger King	Vancouver, WA	2.7	1.2	2.4	20	7	130	22
McDonald's	North Bend, WA	4.1	2.4	3.1	15	19	134	-13
Grocery								
Tieton	Yakima, WA	3.3	2.9	3.7	34	16	54	-25
Thriftway	Beaverton, OR	41.6	1.5	2.5	36	27	46	5
School								
Marsing	Marsing, ID	31.4	5.5	5.8	30	37	10	-3
Edgerton	Kalispell, MT	55.7	31.1	53.7	31	10	13	-6
Miscellaneous								
Waves Motel	Cannon Beach, OR	3.3	—	—	30	—	24	110
O'Ryan Industries	Vancouver, WA	6.0	—	—	49	—	19	124
Boardwalk	Olympia, WA	12.6	—	—	38	—	45	142
Rogers Honda	Albany, OR	13.3	—	—	31	—	24	106
Riverpark Center	Eugene, OR	47.0	—	—	33	—	20	13
Average					35	17		40

— indicates data are not available. "na" indicates data are not applicable (because of negative energy savings).

(a)Both CCE estimates are BPA-funded measures only. The LBL CCE has been adjusted for consistency as described in the text.

(b)% savings estimates for restaurants, grocery stores, and Waves Motel include all end-uses because measures affected non-MCS code end-uses such as cooking (e.g., McDonald's was predicted to save 42% of the MCS end-uses, but only 15% of whole-building energy use); for other building types plug loads and non-MCS end-uses are excluded.

(c)EUI: Energy-Use Intensity. Tuned EUIs are shown for buildings that received Tuned models. The most recent year of electricity data was used for the EUI of the other buildings. 19 are all-electric. Some gas is used in the following buildings (see Chapter 2): Boardwalk, Burger King, Director, Montgomery, Tieton, Riverpark, Skippers, Thriftway, and Tieton.

Many of the measures in the buildings with the lowest energy-use intensity (EUI) were found to be the least cost-effective (e.g., Hollywood, Siskiyou, STS). The analysis of the cost data also indicated that the costs for the measures at STS, the least cost-effective set of measures, were much higher than other similar measures (see Chapter 3). Conversely, many of the measures in the buildings with the highest intensities were the most cost-effective (e.g., McDonald's, Tieton, Thriftway). This suggests that the Tuned model evaluation methodology may be biased toward buildings with higher energy use. This may simply be because it is easier to save energy at a low cost when more energy is being used. The building that illustrates this problem most clearly is Eastgate, which used more energy than any other office, yet the measures were found to be the most cost-effective. The Comparison building evaluation approach concludes, for example, that buildings with high EUIs saved less energy than those with low EUIs.

Differences Between Design-Phase and Tuned Models

Inconsistencies in reporting of the Design-phase assumptions hampered our abilities to definitively explain why the Design-phase predictions of energy savings differ from Tuned model results. There are several reasons for differences between Design-phase and Tuned energy savings. Not all of the measures in the Design-phase predictions were installed in each building. In a few cases, additional measures were added that were not in the prediction. Many measures included in the actual buildings were not included in the Tuned model because of measure failure, partial measure failure, or ambiguity regarding modeling methods. Measure characteristics for both the Base and the Energy Edge systems changed from the Design-phase prediction to the actual building. Building conditions that influence energy use, such as equipment loads and schedules, changed. Modeling techniques differed between the Design-phase and Tuned models. And, measures failed because of poor equipment characteristics, installation, or operating conditions. Differences between the Design-phase and Tuned models are further reviewed in Chapter 5.

We found many significant differences between the Base systems defined in the Design-phase and Tuned models. For example, at East Idaho, the Design-phase Base window system used to assess the Low-E windows was a single-paned window. In the Tuned model the Base is a double-paned window. Therefore, the energy savings from the Tuned model will be less than from the Design-phase model because the Tuned Base is a more energy-efficient technology. Similarly, we also found differences in both the Base and the Energy Edge insulation values in most of the buildings. Differences in hours of use also complicate the comparisons. Another example: the Design-phase prediction for this convenience store was based on 24-hour operation and the actual building operated 16 hours per day.

Assumptions used in the Tuned models were more closely scrutinized than assumptions in the predictions because data from the actual buildings were available and documentation standards were higher. There was also more consistency among the Tuned models because of all of the models were done with DOE-2 and fewer modelers were involved.

Comparison of Design-Phase and Tuned Measure Performance

As described above, many of the measures evaluated as a complete package within each building, did not meet the levelized cost criteria. We found similar results in assessing the predicted CCEs as we did in looking at Tuned CCEs: seven of the 18 predicted CCEs did not meet the target of 5.6 ¢/kWh (Table 1.2). Predicted CCEs for the package of BPA-funded measures range from 0.6 to 18.4 ¢/kWh, a smaller range than that of the Tuned model results.

Design-phase predicted CCEs cannot be directly compared with the Tuned CCEs because for most of the buildings they represent a different set of measures, as discussed above. The last two columns in Table 1.2 show the Tuned and predicted CCEs for the same sets of measures. The set of "like" measures are identical to the full set of "all" measures for four buildings (Tieton, Edgerton, STS, and Burger King). However, the Tuned and Design-phase predicted CCEs are not always closer for the like set of measures than for all measures. They are closer for five buildings (Bellevue, Thriftway, Siskiyou, and McDonald's).

Table 1.2. Measure Cost Effectiveness from Predicted and Tuned Models.

	Cost of Conserved Energy—CCE *(¢/kWh)*					
	All Measures[a]			Like Measures[b]		
Building	**Tuned**	**LBL**	**Predicted**	**Tuned**	**Predicted**	**Type of Cost Data**
Small Office						
Siskiyou	28.7	31.0	6.3	9.5	6.0	Combination
Hollywood	23.5	30.7	10.0	33.1	5.8	Standard
STS	67.4	67.8	9.5	67.8	9.5	Reported
East Idaho	17.4	23.6	5.7	23.6	5.7	Standard
Dubal Beck	7.3	11.2	5.3	11.2	5.5	Reported
Landmark	14.0	10.4	6.9	8.0	5.3	Standard
West Yakima	na	na	3.0	na	na	Not complete
Large Office						
Eastgate	4.3	11.3	5.2	11.2	5.5	Standard
EPUD	15.5	9.9	18.4	7.9	18.4	Standard
Director	8.0	12.0	4.0	11.9	3.8	Standard
Bellevue	na	na	4.5	5.9	3.6	Standard
Fast-Food						
McDonald's	2.4	3.1	4.4	3.1	3.0	Combination
Burger King	1.2	2.4	2.0	2.4	2.0	Reported
Retail						
Evergreen	11.4	2.9	2.9	14.3	7.3	Standard
Grocery						
Tieton	3.3	3.7	1.4	3.7	1.4	Standard
Thriftway	1.5	2.5	0.6	2.5	2.4	Standard
School						
Marsing	5.5	5.8	6.4	4.4	6.4	Standard
Edgerton	31.1	53.7	4.8	53.7	4.8	Standard

[a] "All Measures" are the BPA-funded measures included in either the Tuned or Design-phase models, which may differ.

[b] "Like Measures" are the BPA-funded measures that are an identical set in both the Tuned and Design-phase models (although the characteristics of the measure may have changed).

1.4 Net Program Energy Savings

One objective of the evaluation was to determine the total energy savings from the program. The is a difficult task because the data sets used to derive the savings estimates are not complete. Therefore, we have approached the task by producing several estimates of total savings and describing the biases each method holds. The range and distribution of the results provide more confidence in the overall findings than any individual estimate might provide. Further details on the net energy savings calculations are presented in Appendix A1.

Net Savings Estimation Methods

To obtain an indication of how successful the project is in meeting its goals the first estimate of net energy savings is based on the Design-phase predicted energy savings generated before the buildings were built. This estimate is compared with energy savings based on post-occupancy data from the Tuned models and the Comparison buildings. We have also generated an estimate of the savings that would have been surmised without any of the post-occupancy analysis using the Design-phase Base for comparison with the actual utility bills. Further details on each method are as follows:

- **Design-Phase Predicted Estimate.** This prediction of the total program savings, is simply the difference between the hypothetical Design-Phase Base and the Energy Edge energy-use intensities. Predicted energy savings estimates are available for all buildings.
- **Tuned Model Estimate.** The second estimate extrapolates energy savings from the 18 Tuned models to all 28 buildings. Average savings by building type are used to fill in energy savings estimates for buildings that were not evaluated with Tuned models. Since there were not Tuned models for any of the five miscellaneous buildings, energy savings estimates for these five buildings are filled using the average energy savings (per unit floor area) for the other 23 buildings.
- **Comparison Building Estimate.** The Comparison building estimate is useful because it allows us to consider how the energy use of each building compares to a typical building that might have been built without the efficiency measures during the mid 1980s. The Comparison building estimates further described in Chapter 2 are listed in Table 1.3, along with the average Energy Edge EUIs for each building type. The difference between the the EUI of the Energy Edge building derived from utility bills and the EUI of the Comparison building EUI is the energy savings. The EUI for the Energy Edge buildings are based on the most recent year of utility billing history. Several buildings used more than the comparison buildings, as shown in Chapter 2. There is no Comparison building EUI for the miscellaneous buildings because of their unique and diverse nature. We have prorated average savings from the other 23 buildings to derive an estimate for the five miscellaneous buildings. The Comparison building evaluation method is perhaps the most crude approach we explored because we have identified a single EUI target for each building type (list for each building in Table 1.1). Differences in climate, building characteristics, and occupancy patterns are ignored with such a simplistic approach. The strength of this method is that it allows us to compare the energy use of the Energy Edge buildings against a typical EUI for the respective building type.

Table 1.3. Average Energy-Edge and New Construction Comparison Building Electric Energy-Use Intensities

	Restaurant	Grocery	Small Office	Large Office	School	Retail
Energy Edge Sample (n=)	3	2	8	7	2	1
Avg. Energy Edge EUI (kWh/ft^2-year)	108	50	11	18	12	22
Comparison EUI (kWh/ft^2-year)	130	70	19	21	18	18

Sources to derive these estimates are described in Chapter 2.

- **Design-phase Base Estimate.** Another method to estimate total savings is to compare the actual energy use from utility bills with the Design-phase Base. This technique shows how much savings we might have estimated if the Tuned model evaluation was not conducted. In practice the actual buildings differ from the assumptions in the early Design-phase models. These difference are not accounted for in this simplistic comparison.

Net project savings estimates were based on extrapolating energy savings from buildings of the same type to buildings where the savings were missing. We extrapolate based on average *energy-use savings intensities* (kWh/ft^{2}year) by building type because energy savings intensities vary by building type. Groceries and restaurants, for example, are more energy intensive than the other building types because of refrigeration, cooking, and water heating equipment. These end uses are addressed by some of the energy-efficiency measures.

The energy savings estimates include both BPA-funded and owner-funded measures, although the costs account only for the BPA-funded measures. Energy savings estimates are for electricity use only. Gas use is minimal, and is not included in the net savings (but is described in Chapter 2).

We used two methods to estimate energy savings for buildings where the data are missing. One method uses floor weighting, and the second uses building weighting. Floor area weighting causes the results for the large buildings to dominate the net savings. Further details on the extrapolation methods and results from application of the methods are provided in Appendix A1, which includes a flow chart of the data analysis methodology and several tables of intermediate results.

Net Energy Savings Results

The Design-phase predicted estimates of energy savings for all 28 buildings are 17.3 GWh/year (or 17,300,000 kWh/year) for the building weighted method and 17.1 GWh/year for the area weighted average. These results are shown in Table 1.4. The two estimates of savings from the Tuned models amount to 58% (or 9.9 GWh/year) of the Design-phase predicted savings for the building weighted estimate, and only 13% (2.2 GWh/year) for the area weighted. The large difference in savings derived from the two methods is a result of the influence that large buildings have on the area weighted results. The 389,000 ft^2 Bellevue office building, the largest of the Tuned buildings (more than all others combined), had a net increase in energy use compared to the Tuned Base. One reason for this is the building used a thermal energy storage, which reduced peak capacity demands, but not energy.

Net energy savings from the Comparison building method yields greater savings than the Tuned model savings with 71% and 18% of the Design-phase predictions for the two approaches. The Comparison building EUIs were, therefore, greater than the Tuned Base EUIs, though not dramatically different, offering a check on results from the Tuned models.

The estimate of savings based on comparing the Design-phase predicted Base with utility bills shows much lower savings of 39% of the Design-phase predicted savings for the building weighted approach. It is perhaps the most simplistic of the three savings estimate techniques because the early design estimates have been shown (as described in Chapter 2) to be poor predictors of the building energy performance. There were no savings, rather a net increase in energy use for the area weighted approach. This is because the two largest buildings consumed more energy than their Design-phase MCS Base estimates. The largest building in Energy Edge (and the second tallest in Seattle), is the 1,089,000 ft^2 Gateway Tower building. This building alone accounts for 39% of the built area included in Energy Edge. With actual energy use at 25 kWh/ft^2-year, it consumed 6 kWh/ft^2-year more than the original Design-phase Base.

Table 1.4. Net Program Energy Savings Estimates and Cost Effectiveness for all 28 Buildings.

Scenario	Net Energy Savings *(GWh/year)*	Energy[b] Savings *(kWh/ft^2year)*	% Saved from Pred.	Total Incentive Cost *($M)*	Program Delivery Costs *($M)*	First[b] Cost *($/$ft^2$)*	Net[a] CCE *(¢/kWh)*
Building Weighted							
Design-phase pred.	17.3	6.2		4.1	1.6	2.1	2.9
Tuned models	9.9	3.6	58%	4.1	1.6	2.1	5.0
Comparison buildings	12.2	4.4	71%	4.1	1.6	2.1	4.0
Design Base - bills	6.7	2.4	39%	4.1	1.6	2.1	6.7
Area Weighted							
Design-phase pred.	17.1	6.2		4.1	1.6	2.1	3.0
Tuned models	2.2	0.8	13%	4.1	1.6	2.1	22.3
Comparison buildings	3.1	1.1	18%	4.1	1.6	2.1	16.4
Design Base - bills	4.5	-1.6	-26%	4.1	1.6	2.1	na

All costs are in $1991 (throughout the report).

[a] Assuming a 3% discount rate and a 15-year measure lifetime.

[b] Total floor area in program: 2,779 kft^2.

na - not applicable

Figure 1.1 shows the Design-phase predicted and three post-occupancy net energy savings estimates listed in the previous table. The dominance of the large offices on the total savings is evident.

Figure 1.1 shows the Design-phase predicted and three post-occupancy net energy savings estimates listed in the previous table. The dominance of the large offices on the total savings is evident.

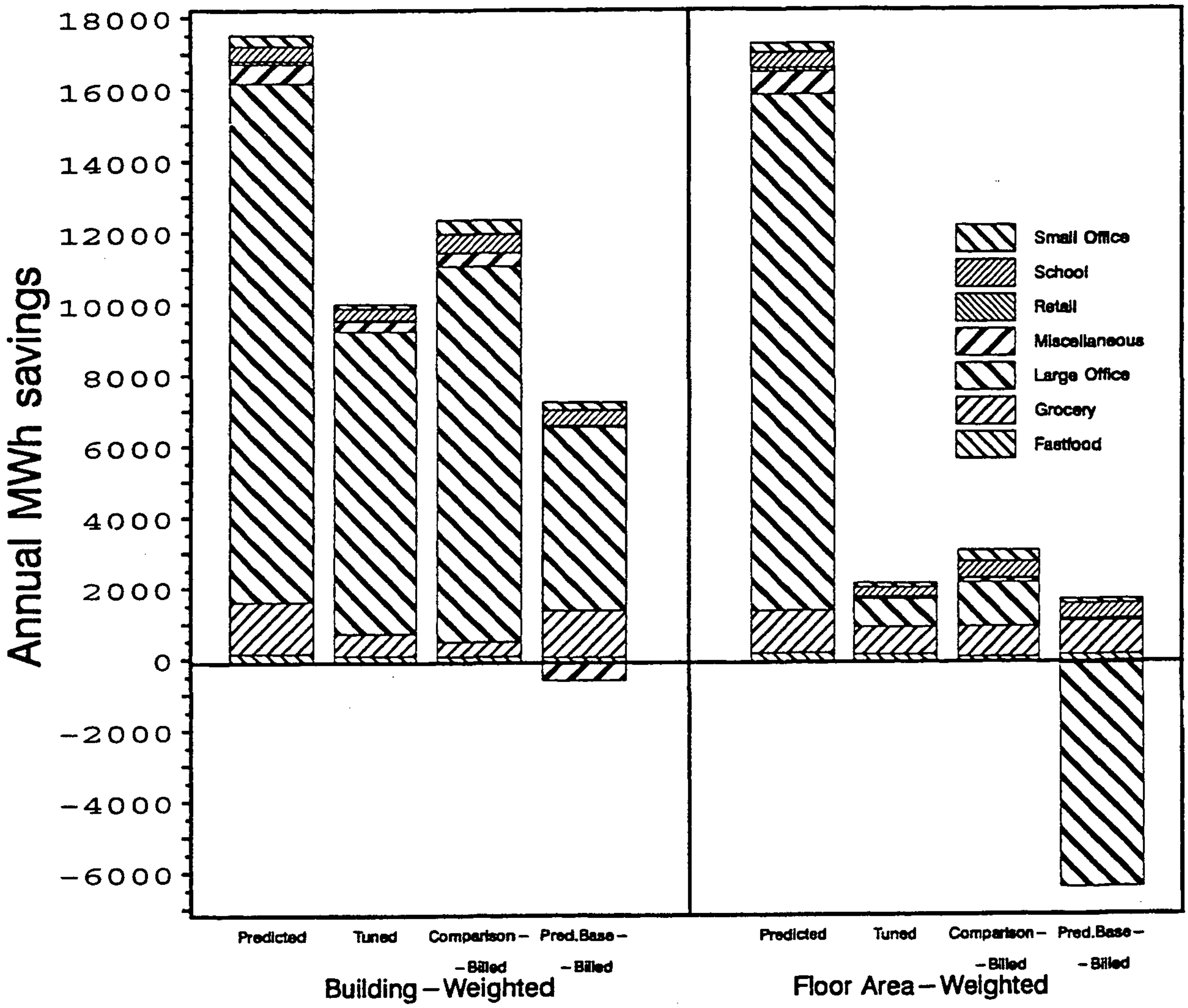


Figure 1.1 Design-Phase Predicted and Post-Occupancy Estimates of Net Energy Savings for 28 Buildings. Post-occupancy estimates were derived using three techniques: 1) extrapolating from the 18 Tuned models to all 28 buildings, 2) using Comparison building EUIs to derive savings, and 3) subtracting actual billed energy use from the Design-phase predicted baselines. Two methods of deriving savings were explored: building and area-weighted results. The large offices dominate the results.

1.5 Net Program Costs and Cost Effectiveness

BPA spent $14.6 million on the Energy Edge project[4]. This total includes costs for metering, administrative costs, evaluation activities, data management, and modeling. The largest expense (32%) was for the four sponsors to administer the program, which involved conducting the competition, working with the building owners and design teams, tracking the installation of measures and subsequent monitoring, and conducting the operations and maintenance audits. Table 1.5 shows how the costs were divided among the project activities. Unlike other tables in the report, these costs are mostly in 1988 and 1989 dollars. About one-fourth of the total costs were spent on the energy-efficiency measures ($3.6 million). Again, the costs spent on the large buildings account for the largest fraction of the costs.

---

[4] Nominal dollars spent between 1986 and 1993.

Table 1.5. Total Costs for the Energy Edge Program.

Cost Category	**Cost** *(k$)*	**Percent**
Sponsor's Activities	4,678	31.8
Efficiency Measures Incentives	3,555	24.2
Metering	2,101	14.3
BPA Administrative Costs	1,573	10.7
Impact Evaluation	1,197	8.2
Data Management	582	4.0
Process Evaluation	378	2.6
Tuned Modeling	360	2.5
Occupant Satisfaction Evaluation	108	0.7
STEM One-Time Tests	63	0.4
Measure Cost Analysis	55	0.4
Design Documentation	33	0.2
Total	14,683	100.0

We can combine the energy savings estimates discussed above with the program cost data to estimate the total cost-effectiveness of the program. As a research-oriented program, it would not be appropriate to consider all of the program costs in an estimate of net program cost-effectiveness. The monitoring, modeling, and evaluation activities in Energy Edge greatly surpass the costs for such activities in typical demand-side management programs.

Experience with BPA's commercial programs has shown that program delivery costs are about 35 to 40% of the cost of efficiency improvements[5]. In the estimates of net program cost-effectiveness (listed in Table 1.4) we add an additional 40% increase (or $1.42 million) to the incentive costs to account for program delivery costs. These costs are only for the measures that BPA funded; many of the owners paid for additional energy efficiency measures identified in the design studies that went beyond the MCS code requirements. The costs for the measures and program delivery, adjusted from $1988 to $1991 based on the Consumer Price Index (U.S. Bureau of the Census, 1992) sum to $4.1 and $1.6 million respectively.

Total program costs are combined with the energy savings estimates to calculate a cost of conserved energy (CCE) using a 3% discount rate. Results from the Tuned models indicate that the aggregate average measure life was about 14 years. For simplicity, we assume a 15-year lifetime in the net cost-effectiveness estimates. The CCEs are shown in Table 1.4.

The net savings analysis has shown that the cost effectiveness of the project was not as great as predicted. This is because energy savings were less than predicted. In general, the measures cost about as much as predicted to actually install. The CCEs for the Design-phase predicted savings are 2.9 ¢/kWh and 3.0 ¢/kWh, well below the 5.6 ¢/kWh target. The Tuned model CCEs derived using the building weighting method at 5.0 ¢/kWh also meet the target, although the area weighted estimate at 22.3 ¢/kWh is four times greater than the target. Since the Comparison building estimates resulted in greater savings than the Tuned model estimates, the CCEs are correspondingly lower at 4.0 ¢/kWh and 16.4 ¢/kWh. Finally, the CCEs estimated from comparing actual energy use from utility bills with the Design-phase predicted baseline estimates results in a CCE of 6.7 for the building weighted case; there is no CCE for the area weighted case because there were no net savings because the largest building used more than the Design-phase baseline[6].

---

[5] Personal communication from Bruce Cody, Bonneville Power Administration, December, 1993.

[6] Negative CCEs are often produced when the costs to install an energy-efficiency measure are less than the basecase system because of savings such as reduced operations and maintenance costs.

Chapter 2. Building Performance

Key Findings

- On average, energy use increased during the first four years of operation, though the rate of growth slowed each year. Fourth year energy use was six percent greater than third year energy use, with no increase found in the fifth year.
- Energy use in the Tuned models was greater than predicted for two-thirds of the 18 buildings. The greatest increase is from heating, ventilation, and air-conditioning (HVAC) systems using more energy than predicted.
- The Energy Edge small office buildings have lower energy use than similar new buildings, with reductions between 30 and 50%. The lighting and shell characteristics reflect efficient design principles, and are significantly different than common practice, which partly explains their low energy use.

2.0 Introduction

The analysis of the energy performance of the Energy Edge buildings described in this chapter is based on comparison of actual energy use from utility bills, end-use metering, and Tuned models with Design-phase predicted energy use. We also compared actual energy use and building characteristics data to similar data for new buildings and prototypes in the Pacific Northwest. Originally the program designers thought the most important comparison would be between the Energy Edge building and the Base defined in the Tuned models. We found that the comparing the energy use of the Energy Edge buildings with regional trends was crucial to provide a benchmark and context for the building performance data from the Tuned models. The challenge in defining the appropriate baseline moves beyond code comparisons and asks: “What would have been built without Energy Edge?” and “What is common practice?”

The chapter begins with a comparison of actual energy use from long-term utility billing histories with Design-phase predictions of energy use. In the second section we look beneath the whole-building data to the end-use data to understand which building systems are responsible for the difference between design-predicted and actual energy use. The third section focuses on the performance of the seven small office buildings compared with other regional office buildings data. Although the sample is small, we believe that the data illustrate several important trends for energy-efficient small offices. Furthermore, the detailed glimpse into one building type shows how information on building characteristics help explain energy consumption trends. The fourth section compares energy use of the other building types with other regional new construction data. For each building type (except the miscellaneous buildings) we estimated a single whole-building energy-use intensity (EUI in kWh/ft^{2}year) used in the Comparison building net savings estimates described in Chapter 1. The final section in this chapter summarizes results from surveys of occupant satisfaction conducted at seven offices.

2.1 Comparing Actual to Predicted Energy Consumption

Energy Use Over Time for all 28 Buildings

It is important to examine how energy use changes over time because new buildings may take several years to reach full occupancy and stable energy use patterns. Up to six years of utility bill data have been compiled for the Energy Edge buildings. Three years of data are available for all 28 buildings, and five years are available for 21 buildings.

On average, energy use increased during the first four years post occupancy, climbing to 36% more than the Design-phase predictions, as shown in Table 2.1[1]. Second-year energy use was 18% greater, on average, than the first year of utility bills. After the third year the growth slowed to 7%, and only eight buildings were using less than Design-phase predicted energy use. The increase slowed slightly in the fourth year 6% annual growth.

---

[1] Two different averages are show in the table, the first of which is quoted in the text. The first is the average of the ratios of EUIs compared with the previous of the Design-phase predicted EUI; large ratios dominate the average. The second average is the ratio of the averages, dominated by high EUIs (such as Burger King or McDonald's.)

Table 2.1 Changes in Annual Billed Electrical Consumption—All Buildings

BUILDING NAME	Billing Started	Energy Edge EUI (kWh/ft^{2}year)		ANNUAL CHANGES										
				1st to	2nd to		3rd to		4th to		5th to		6th to	
		Pred	1st Year	Pred	1st	Pred	2nd	Pred	3rd	Pred	4th	Pred	5th	Pred
Bellevue	05 89	20.90	17.90	0.86	1.02	0.87	1.20	1.05	—	—	—	—	—	—
Boardwalk	07 88	18.50	33.00	1.78	1.11	1.98	1.12	2.22	1.09	2.42	—	—	—	—
Burger King	09 88	107.00	112.10	1.05	1.04	1.09	1.08	1.17	1.04	1.22	—	—	—	—
Caddis	11 86	9.00	8.80	0.97	0.69	0.67	1.30	0.87	1.17	1.02	1.14	1.17	0.94	1.09
Director	03 88	10.00	2.70	0.27	3.37	0.92	1.31	1.21	0.98	1.19	0.98	1.16	—	—
Dubal	06 87	10.10	13.20	1.31	1.05	1.37	1.05	1.44	0.95	1.37	0.91	1.24	—	—
Eastgate	07 87	8.40	10.10	1.20	1.75	2.10	0.87	1.81	1.13	2.04	1.01	2.07	—	—
East Idaho	04 87	9.10	15.40	1.69	1.05	1.78	0.89	1.59	0.99	1.57	0.97	1.53	—	—
Edgerton	08 87	14.10	14.80	1.05	0.97	1.02	0.95	0.97	1.06	1.03	0.87	0.90	—	—
EPUD	02 89	7.60	11.10	1.46	1.07	1.56	0.87	1.36	1.00	1.36	—	—	—	—
Evergreen	11 87	15.70	8.60	0.55	1.80	0.98	1.11	1.10	0.99	1.09	0.95	1.03	—	—
EWEB	06 88	25.40	15.60	0.61	1.18	0.73	0.94	0.68	1.15	0.78	—	—	—	—
Gateway	02 90	13.60	22.70	1.67	1.04	1.73	1.04	1.80	—	—	—	—	—	—
Hollywood	09 87	8.30	8.00	0.97	1.06	1.03	0.88	0.91	1.00	0.91	0.98	0.89	—	—
Landmark	02 87	13.90	13.40	0.96	1.05	1.02	1.10	1.12	1.07	1.20	0.89	1.06	1.02	1.09
McDonalds	11 87	156.30	125.30	0.80	1.10	0.88	1.06	0.94	1.02	0.95	0.97	0.92	—	—
Marsing	10 87	9.30	8.90	0.96	1.02	0.98	1.24	1.22	1.07	1.30	1.20	1.56	—	—
Montgomery	10 87	8.20	9.20	1.13	1.48	1.67	1.13	1.89	1.05	1.98	1.03	2.04	—	—
O'Ryan	08 86	8.30	13.10	1.57	1.23	1.95	1.72	3.34	0.82	2.73	0.98	2.67	0.84	2.24
Riverpark	10 87	17.60	18.80	1.07	0.98	1.05	1.02	1.07	1.10	1.17	0.96	1.13	—	—
Roger	12 87	11.70	20.50	1.75	1.08	1.89	1.03	1.96	1.04	2.03	1.01	2.06	—	—
Siskiyou	07 87	10.80	10.60	0.98	0.97	0.95	0.92	0.88	0.96	0.84	1.07	0.90	—	—
Skippers	01 87	35.80	42.50	1.19	1.03	1.22	1.13	1.38	1.18	1.62	0.99	1.60	1.07	1.71
STS	06 87	13.20	15.30	1.16	0.65	0.75	1.05	0.79	1.33	1.05	1.00	1.05	0.86	0.90
Thriftway	10 87	59.30	40.20	0.68	0.99	0.67	0.98	0.66	1.19	0.78	1.02	0.80	—	—
Tieton	04 88	75.40	85.90	1.14	0.95	1.08	0.93	1.01	0.99	1.00	—	—	—	—
Waves	03 87	11.40	21.10	1.85	1.03	1.91	1.05	2.01	1.05	2.11	0.98	2.08	1.01	2.10
W.Yakima	12 86	7.80	10.20	1.31	1.21	1.58	1.02	1.61	1.07	1.72	1.13	1.95	1.04	2.03
N		28	28	28	28	28	28	28	26	26	21	21	7	7
Average 1		25.60	26.04	1.14	1.18	1.27	1.07	1.36	1.06	1.40	1.00	1.42	0.97	1.59
Average 2		0.00	0.00	1.02	1.07	1.08	1.06	1.15	1.06	1.22	0.80	0.98	0.90	0.87
Std. Dev.		33.8	30.2	0.386	0.5	0.446	0.2	0.568	0.1	0.525	0.3	0.618	3.0	3.044

Increases in energy use dropped off in the final years of data for the sample of buildings with the most complete billing histories. By the fifth year energy use is 42% greater than Design-phase predicted for the 21 buildings with five years of data. Relative to year four, however, the average consumption is essentially the same. Six years of data are available for seven buildings, showing for the first time a net decrease in energy consumption. Compared to year five, the average consumption for the six buildings is 3% less than in the previous year. We have not accounted for changes in weather or occupancy. We did not have access to information on start-up occupancy rates that might be correlated with the rate of growth in energy use.

Energy Use over Time for Office Buildings

We have looked in greater detail at energy use patterns of the fifteen office buildings, as plotted in Figure 2.1 and listed in Table 2.2. The data in the figure are 12-month rolling averages[2]. Compared to the total sample of 28 Energy Edge buildings, energy use for the office buildings is closer to Design-predicted consumption. By the third year, the growth rate relative to the previous year for the offices was only 4%, almost half that of the 28-building set (7.1%). Figure 2.1 shows how energy use for the 15 changed over time, comparing the EUIs to other regional office buildings data discussed below in Section 2.3. Average consumption for the 15 office buildings (continuous thick line) is well below the comparison buildings. By the third year average energy use is 19% greater than the Design-phase predicted average as shown in the figure (and in Table 2.2, column eight, Average 2).

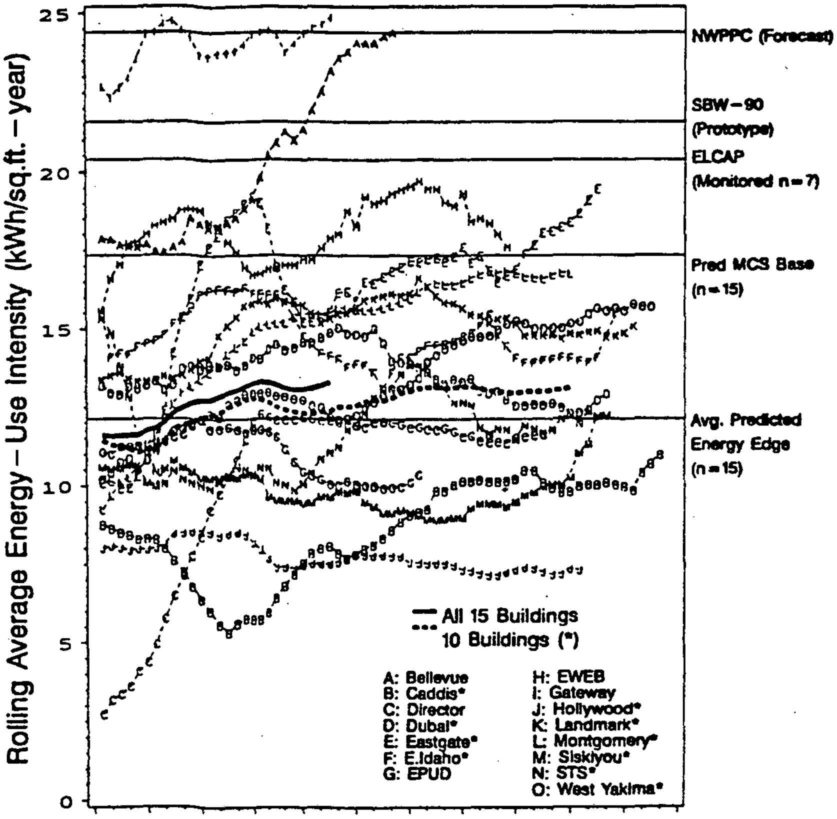


Figure 2.1. Energy consumption over time for 15 Energy Edge Office Buildings with comparison buildings. Data are 12-month moving averages from utiltiy bills. Average EUIs for all 15 buildings and the subsample of 10 buildings with five years of data are shown. ELCAP data are from 7, post-1980, all-electric buildings. NWPPC are the 1989 forecast numbers for new construction. SBW-90 are prototypes based on 1989 common practice.

---

[2] Each point is the sum of the previous 12-month's energy use, normalized by floor area.

Table 2.2 Changes in Annual Billed Electrical Consumption—Office Buildings Only

BUILDING NAME	Billing Started	Energy Edge EUI (kWh/ft^{2}year)		ANNUAL CHANGES										
				1st to	2nd to		3rd to		4th to		5th to		6th to	
		Pred	1st Year	Pred	1st	Pred	2nd	Pred	3rd	Pred	4th	Pred	5th	Pred
Bellevue	05 89	20.90	17.90	0.86	1.02	0.87	1.20	1.05	—	—	—	—	—	—
Caddis	11 86	9.00	8.80	0.97	0.69	0.67	1.30	0.87	1.17	1.02	1.14	1.17	0.94	1.09
Director	03 88	10.00	2.70	0.27	3.37	0.92	1.31	1.21	0.98	1.19	0.98	1.16	—	—
Dubal	06 87	10.10	13.20	1.31	1.05	1.37	1.05	1.44	0.95	1.37	0.91	1.24	—	—
Eastgate	07 87	8.40	10.10	1.20	1.75	2.10	0.87	1.81	1.13	2.04	1.01	2.07	—	—
East Idaho	04 87	9.10	15.40	1.69	1.05	1.78	0.89	1.59	0.99	1.57	0.97	1.53	—	—
EPUD	02 89	7.60	11.10	1.46	1.07	1.56	0.87	1.36	1.00	1.36	—	—	—	—
EWEB	06 88	25.40	15.60	0.61	1.18	0.73	0.94	0.68	1.15	0.78	—	—	—	—
Gateway	02 90	13.60	22.70	1.67	1.04	1.73	1.04	1.80	—	—	—	—	—	—
Hollywood	09 87	8.30	8.00	0.97	1.06	1.03	0.88	0.91	1.00	0.91	0.98	0.89	—	—
Landmark	02 87	13.90	13.40	0.96	1.05	1.02	1.10	1.12	1.07	1.20	0.89	1.06	1.02	1.09
Montgomery	10 87	8.20	9.20	1.13	1.48	1.67	1.13	1.89	1.05	1.98	1.03	2.04	—	—
Siskiyou	07 87	10.80	10.60	0.98	0.97	0.95	0.92	0.88	0.96	0.84	1.07	0.90	—	—
STS	06 87	13.20	15.30	1.16	0.65	0.75	1.05	0.79	1.33	1.05	1.00	1.05	0.86	0.90
W.Yakima	12 86	7.80	10.20	1.31	1.21	1.58	1.02	1.61	1.07	1.72	1.13	1.95	1.04	2.03
N		15	15	15	15	15	15	15	13	13	11	11	4	4
Average 1		11.75	12.28	1.10	1.24	1.25	1.04	1.27	1.07	1.31	1.01	1.37	0.96	1.28
Average 2		0.00	0.00	1.04	1.11	1.16	1.03	1.19	0.96	1.13	0.98	1.11	1.01	1.12
Std. Dev.		5.0	4.6	0.361	0.6	0.442	0.1	0.392	0.2	0.427	0.4	0.565	2.8	2.786

"Average 1" is the average of the above ratios.
"Average 2" is the ratio of the average EUIs.

Gas Consumption

The Energy Edge program was designed to assess conservation potential in all-electric buildings. However, although none of the Energy Edge buildings use gas as their primary heating system, some use gas for back-up heat (Director and Montgomery), several have gas cooking (Tieton, Thriftway, Burger King, Skipper's, and Boardwalk) and one has gas water heating for laundry (Riverpark). Figure 2.2 shows the 12-month moving average gas consumption for these eight buildings in kBtu/ft^2-year. Gas energy use does not change much over time for most of the buildings. The exceptions are Boardwalk and Skipper's, where gas use climbs steadily over the first few years.

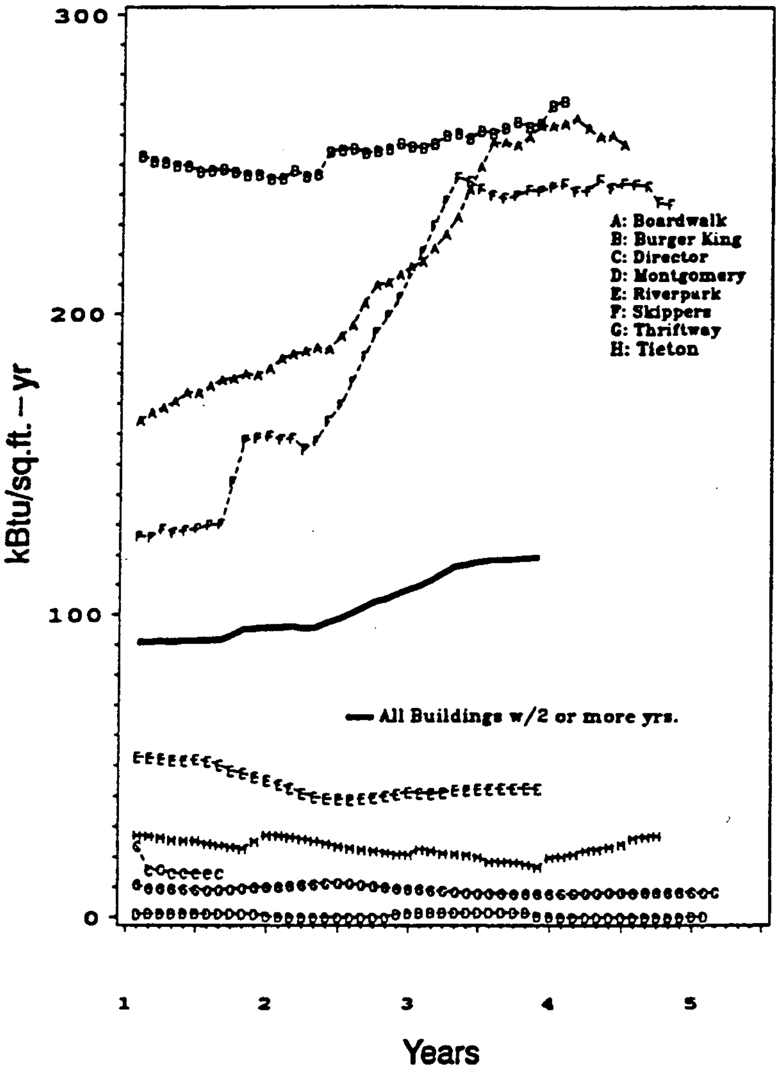


Figure 2.2. 12-month Rolling Average Gas Consumption Over Time of 8 Energy Edge buildings.

2.2 Energy End-Use Trends

Hourly energy end-use data were collected for 24 buildings in Energy Edge, although only a few months of data were collected for several buildings. End-use data indicate how energy is used within the building. This section first discusses how the end-use breakdowns compared with Design-phase end-use breakdowns. Second, we discuss how the end uses changed over time. The end-use monitoring generally took place for one to two years. To compare energy end-use intensities we divide the whole-building energy use into three general end-use categories: HVAC, Lighting, and Other. "Other" includes miscellaneous loads such as water heating, exterior lighting, and plug loads, plus refrigeration and cooking in restaurants and grocery stores. Appendix B provides graphs of the monitored end-use data.

Differences in Predicted and Tuned End-Use Intensities

It is useful to compare energy use in the actual building with the Design-phase prediction. Total Tuned model energy use was greater than predicted for 12 of the 18 buildings as shown in Table 2.3. Tables 2.4 presents HVAC energy use for the Design-phase Predicted (Base and Edge), Tuned (Base and Edge), plus monitored energy use for a selected period. The most significant trend is that HVAC energy use was underpredicted. HVAC energy use in the Tuned Energy Edge buildings was greater than predicted for 14 of the 18 buildings. We do not see this same trend in the lighting EUIs, where the Tuned Energy Edge lighting EUIs were greater than predicted for 11 of the 18 buildings. The predictions for the Other end-use category were evenly split with 9 of the 18 greater than predicted. (Tables similar to 2.3 for Other and Lighting are found in Appendix A2.) This suggests that closer attention to HVAC assumptions are needed in design models.

Table 2.3. Total Design-phase Predicted, Tuned, and Monitored End-Use Energy Consumption.

	Predicted		**Tuned**		**Monitored**
	MCS Base *kWh/ft²year*	**Energy Edge** *kWh/ft²year*	**MCS Base** *kWh/ft²year*	**Energy Edge** *kWh/ft²year*	*kWh/ft²year*
Bellevue	27.5	21.8	17.6	18.5	—
Burger King	133.6	106.9	140.7	130.6	—
Director	14.5	10.0	14.6	11.4	—
Dubal Beck	13.5	10.2	16.7	13.4	13.4
Eastgate	13.6	8.6	28.0	21.4	17.3
EPUD	11.6	7.6	18.7	14.0	—
Evergreen	19.8	15.7	23.6	22.5	—
Hollywood	13.3	8.3	11.8	11.2	—
East Idaho	14.0	9.1	16.1	13.9	—
Landmark	19.1	14.2	17.4	14.6	—
Marsing	14.0	10.8	16.2	10.5	—
McDonalds	185.9	157.9	165.0	134.3	139.0
Edgerton	19.8	14.1	14.8	13.3	12.5
Siskiyou	15.6	9.7	12.2	9.0	—
STS	23.32	15.5	12.6	10.8	—
Thriftway	69.2	44.3	63.8	46.5	—
Tieton	110.7	72.9	64.9	54.6	—
West Yakima	11.7	7.8	12.7	11.5	—

Table 2.4. Design-phase Predicted, Tuned, and Monitored HVAC Energy Consumption.

	Predicted		Tuned		Monitored
Building	MCS Base (kWh/ft²year)	Energy Edge (kWh/ft²year)	MCS Base (kWh/ft²year)	Energy Edge (kWh/ft²year)	(kWh/ft²year)
Bellevue	10.8	6.9	4.9	5.9	—
Burger King	49.0	27.2	32.5	28.4	—
Director	6.4	3.8	6.6	4.5	4.8
Dubal Beck	7.2	5.2	8.4	6.5	6.2
Eastgate	5.6	2.5	19.8	15.4	11.2
EPUD	6.1	5.0	11.1	8.2	5.3
Evergreen	6.2	4.2	8.2	8.3	4.1
Hollywood	7.1	3.4	4.7	4.5	4.4
East Idaho	8.2	3.3	9.8	7.6	7.8
Landmark	10.5	6.0	11.5	8.6	9.3
Marsing	5.9	3.6	11.1	7.1	6.2
McDonalds	37.8	21.1	32.8	25.4	27.6
Edgerton	15.3	10.6	9.6	8.7	9.4
Siskiyou	5.3	3.5	7.8	5.0	5.4
STS	15.3	7.4	6.4	4.6	4.3
Thriftway	6.8	3.3	12.2	6.6	6.3
Tieton	10.5	8.7	11.5	8.8	9.8
West Yakima	5.8	2.8	5.1	3.9	4.9

Changes in End-Use Loads Over Time

As discussed above, on average of about four years post-construction passed before energy use leveled off in the Energy Edge buildings. We are unable to identify which end-uses are responsible for the majority of the increases because the end-use data are not available for nearly as long as the utility bills. It is likely that the increases were distributed among the end uses and driven by increases in occupancy. We have examined end-use data from thirteen buildings to examine which end uses were changing over time. In many cases the periods of increase shown in utility bill data are not covered by the end-use monitoring.

Figure 2.3 shows the HVAC end-use over time for 13 buildings. Similar graphs of Lighting and Other end uses are found in Appendix A2. Again the graph shows 12-month moving averages of end-use energy consumption. The HVAC moving average fluctuates quite a bit for most buildings, with a striking downward trend at East Idaho and an upward trend at Marsing. Lighting energy use over time was fairly flat compared to the HVAC changes. The Other end-use was also fairly flat in most buildings, with upward trends at three offices, Caddis, Eastgate, and West Yakima, and a downward trend at two offices: EPUD and Siskiyou. We looked for increases in the other end-use as office equipment such as computers, printers, and copiers were brought in over the first few years of occupancy, but did not identify such a trend[3].

---

[3] Increases in Other energy use were found in some of the buildings. Plug loads accounted for 20% of total energy use in Dubal Beck, growing by 50% during 1988 and 1989. It is unclear if the increase was from task lighting, space heaters, or office information technologies (Harris et al., 1990, p. 8-7).

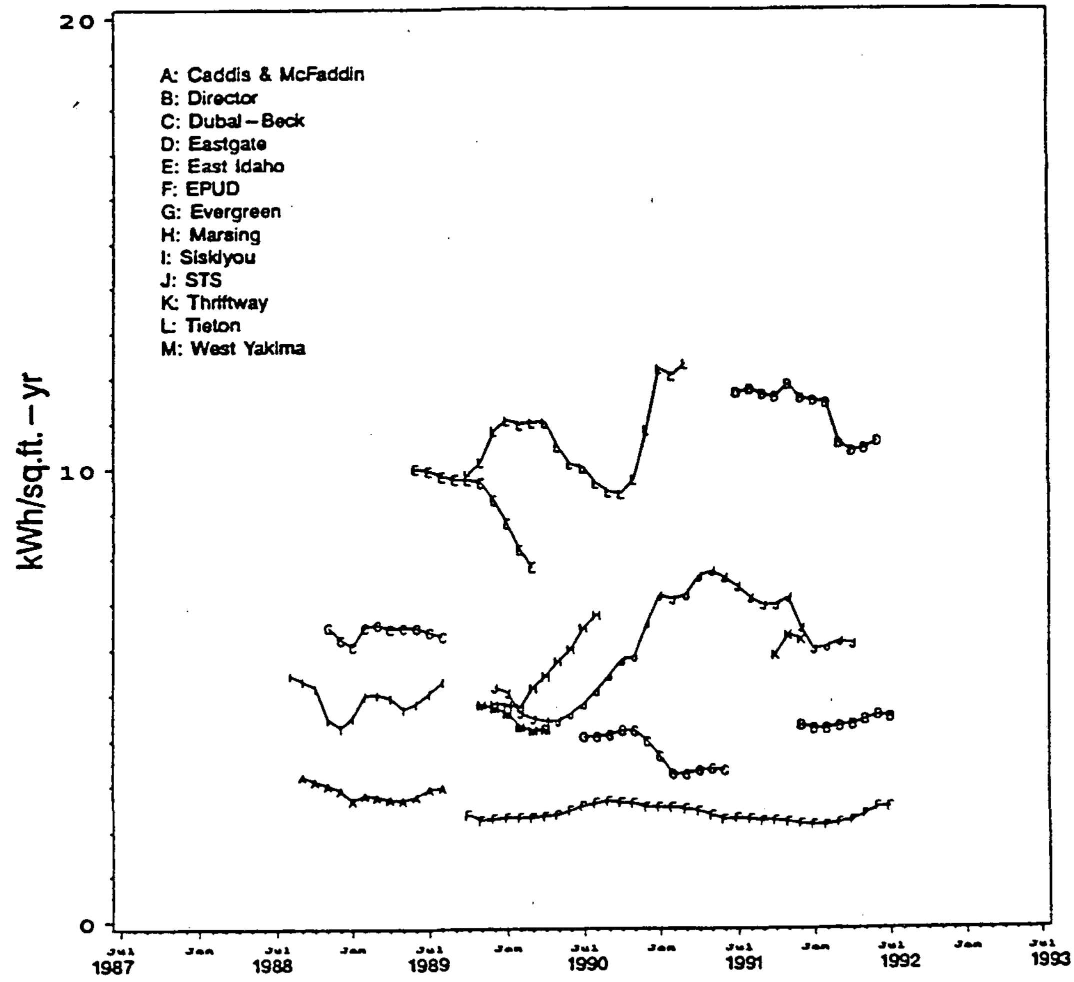


Figure 2.3. Monitored HVAC Energy Consumption—Moving Averages. The 12-month moving average for monitored HVAC EUI in 13 Energy Edge buildings.

2.3 Comparing Energy Edge Small Office Buildings with Regional Buildings

In this section we discuss trends in new office buildings built in the 1980s and 1990 that relate to changes in the regional energy codes. We focus on the small office buildings because these seven Tuned buildings are a more homogeneous sample than the other building types, with comments on large offices. Although the data samples used in the analysis are limited, they suggest that the Energy Edge small offices built in 1986 and 1987 tend to be more energy-efficient than others built during the 1980s. Many of the lighting and shell characteristics in the Energy Edge buildings appear to be as good as, or better, than typical small offices built in 1990. The sources used for this section are as follows:

- **End-Use Load Conservation and Assessment Program (ELCAP).**
  The ELCAP data are from direct analysis of data not cited in published reports, including characteristics and end-use EUIs for small offices built between 1982 and 1984 (Taylor and Pratt, 1989). Energy use and characteristics data for seven small offices are presented; the average area was 11 kft^2. All are in the Seattle area.
- **Pacific Northwest Non-Residential Energy Consumption Survey (PNNonRES).**
  PNNonRES results are from direct analysis of data not cited in published reports (ADM Associates, Inc., 1992 and BR Associates, Inc., 1992). Characteristics of 15 offices, ranging from 3 to 300 kft^2, were used to estimate lighting power densities (excluding parking garages and lots). The buildings were built between 1980 and 1987.

- **SBW Northwest Regional DOE-2 Prototypes.**
  SBW developed building prototypes to simulate typical new buildings used in the regional forecasts of energy use. We examined characteristics and end-use data for the small and large office prototypes (SBW, 1989). Results from three simulations of 1989 practice in the Seattle climate are presented: the 4.8 kft^2 small office with two HVAC types (heat pump and electric resistance heat), and an all-electric 408 kft^2 large office.
- **Code compliance.**
  A recent study of commercial sector code compliance in Oregon and Washington provides building characteristics data for construction practice in 1990 (Kennedy and Baylon, 1992). There were no utility bills collected for these buildings.
- **Major Projects Requirements (MPR) Evaluation.**
  This evaluation compared large offices in Seattle built to the MPR (which is slightly more stringent than MCS) with other local large offices (Katz et al., 1989). The design simulations showed they were designed to be 10% more energy efficient than a building built to the prescriptive code. We present lighting power density (LPD) and EUIs for buildings greater than 75 kft^2 built between 1985 and 1987.
- **Power Council Forecast for Public Utility Offices.**
  Characteristics and end-use EUIs for small offices representing 1990 practice from the Northwest Power Planning Council (NWPPC) are also discussed below (NWPPC, 1991).

Figure 2.4 shows the average energy use by end-use for seven Tuned Energy Edge small offices compared to other regional comparison buildings. The Tuned MCS base is also shown, along with the Design-phase predicted Base and Energy Edge EUIs. On average, the actual Energy Edge buildings consume slightly more than Design-phase predicted, while the Tuned Base buildings use less than the predicted Bases. Total energy savings per building are therefore less than Design-phase predicted.

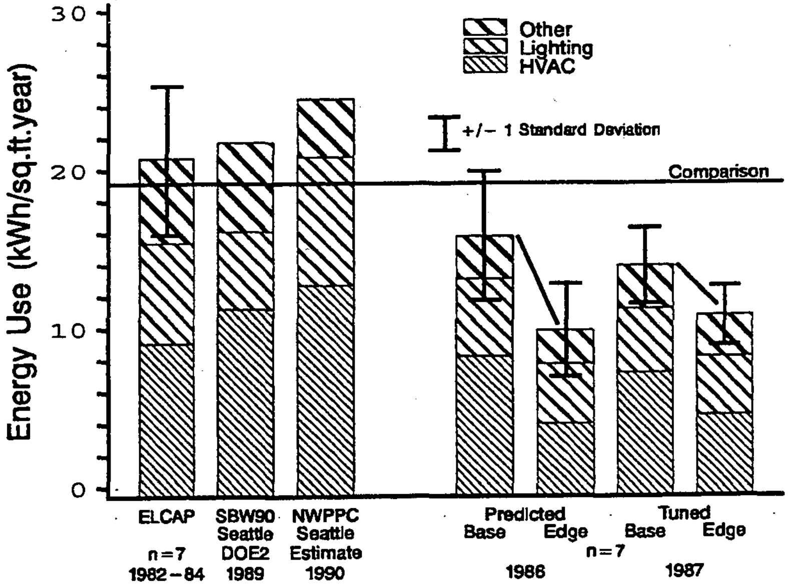


Figure 2.4. End-use Energy Consumption for Seven Small Energy Edge Offices and Comparison Buildings. The buildings are Dubal, East Idaho, Hollywood, Landmark, STS, Siskiyou, and West Yakima. (Data from Tables 2.5 and 2.6).

On the other hand, the Energy Edge small offices use up to 50% less than the comparison buildings. The comparison data in Figure 2.4 include ELCAP, the NWPPC estimate for offices in 1990, and the SBW prototype for 1989 small offices in Seattle with resistance heat. Standard deviations are shown on the figure for the ELCAP and Energy Edge results.

Since the sample sizes are small, we performed some statistical tests to see if the means from the Energy Edge EUIs are significantly lower than the other samples. Table 2.5 shows the z-score and confidence level for five different pairs of small office EUI means from Figure 2.4. Results from the statistical tests indicate that the means from the various small office EUI samples were significantly different. If the means were close together, or the distributions of the population were wide, there is some significant probability we would draw samples that are similar. However, results from the z-score tests indicate we are confident that the means are different. The figure also shows that the standard deviations among the Energy Edge EUIs are actually lower (building energy use is more consistent) for the Tuned results than from the Design-phase predictions. The lowest z-score and confidence level (83%) in the table is the comparison between the Design-phase predicted and Tuned Energy Edge EUIs. The highest z-score (at 100% confidence) is the comparison of the Energy Edge Tuned EUIs compared with the ELCAP EUIs.

Table 2.5. Statistics of Small Office EUI Means and z-Score Tests.

Sample	Mean (x)	Std. Dev. (s)	Z-Score $(x_1-x_2)/A$	Confidence
Tuned MCS Base	14.0	2.3	1.7	95%
Tuned Energy Edge	12.0	1.8		
Design-phase Predicted MCS Base	15.9	3.9	2.65	100%
Design-phase Predicted Energy Edge	10.7	2.8		
ELCAP Average	20.6	4.4	4.4	100%
Tuned Energy Edge	12.0	1.8		
Tuned MCS Base	14.0	2.3	1.0	85%
Design-phase Predicted MCS Base	15.9	3.9		
Tuned Energy Edge	12.0	1.8	1.0	83%
Design-phase Predicted Energy Edge	10.7	2.8		

All samples n=7.

$$A = \sqrt{\frac{s_1^2}{n_1-1} + \frac{s_2^2}{n_2-1}}$$

The key point is that the Tuned average Energy Edge small office EUI (for buildings built in 1986 and 1987) is significantly lower than the comparison data. It is somewhat surprising that the NWPPC and SBW EUIs representing late 1980s and 1990 prototypes are above the average ELCAP small office EUI (early 1980s practice). The difference is probably from variations in heating systems further discussed below. The following sections examine differences among the comparison data for the three major end use categories: Lighting, HVAC, and Other.

Lighting Power Density and Energy Use

Figure 2.5 shows lighting energy use vs. lighting power density (LPD) for several samples of buildings[4]. Several trends are evident. The ELCAP buildings had higher LPDs and higher lighting EUIs than the Energy Edge small offices. Similarly, the MPR large offices had LPDs similar to the Energy Edge small offices, but the EUIs were higher. This is probably because the lights were more often left on during the night in the large buildings. The SBW 1989 large office prototype had a higher lighting EUI than the small office. Many of the Energy Edge buildings had controls, such as occupancy sensors, to reduce lighting hours of energy use. SBW also modeled 1980 practice buildings (not shown), which were assumed to have LPDs of 2.0 W/ft^2. The average PNNonRES LPD for small offices built between 1980 and 1985 was 2.2 W/ft^2, and the average for large offices was 1.8 W/ft^2.

---

[4] We found that monitored lighting was about 15% less than rated, so equivalent on-times are greater than the 30% and 50% lines suggest.

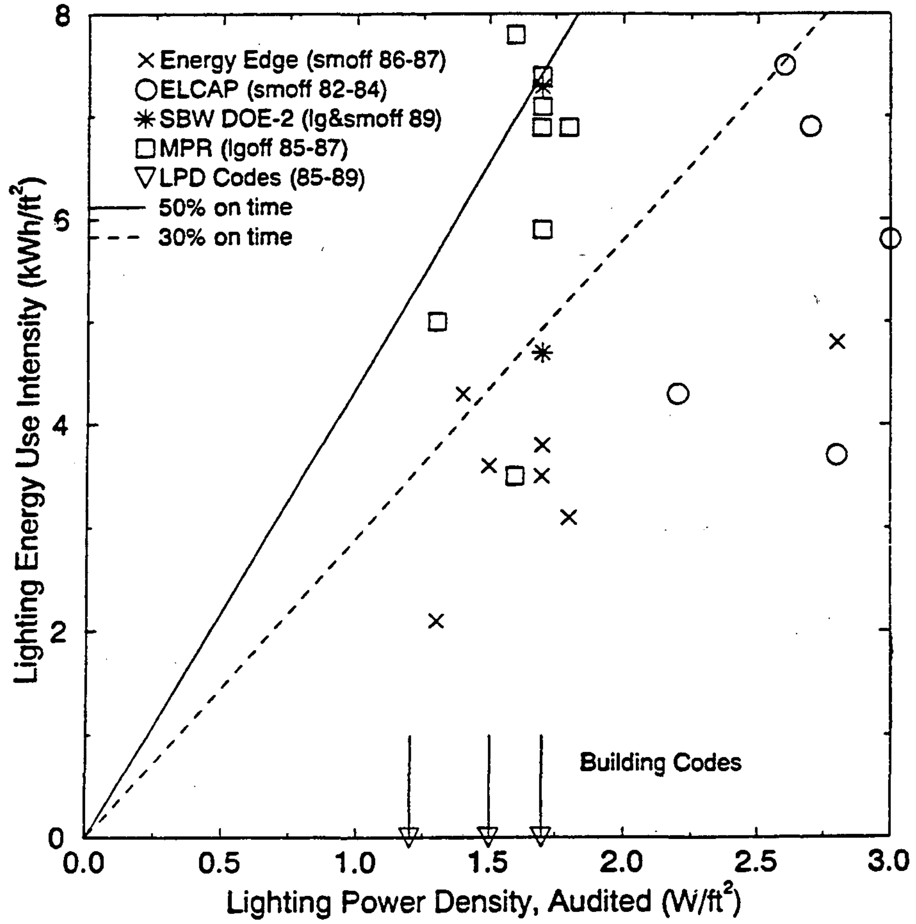


Figure 2.5. Lighting Energy Use vs Power Density for Offices. The lighting systems in the Energy Edge small offices are lower-energy systems than typical buildings built in the mid-1980s.

The figure shows several LPDs from the building codes for offices: 1.7 W/ft^2 for Washington and Oregon, 1.5 W/ft^2 for the 1985 MCS code, and 1.2 W/ft^2 for the new MCS (1989). None of the small offices in Energy Edge buildings met the new MCS requirement. One large Energy Edge office met the new MCS[5].

LPDs from a recent code compliance study for 1990 practice are similar to those for Energy Edge. For the 12 small offices from Oregon and Washington the median LPD is 1.5 W/ft^2. The code study found that LPDs for large offices were even lower, though the sample size was small.

Overall, the data suggest that the lighting systems in the Energy Edge small offices are lower-energy systems than typical buildings built in the mid-1980s. The LPD used in the Energy Edge Tuned models for the Base MCS buildings is 1.5 W/ft^2, lower than typical buildings built in 1986. Based on the data in Figure 2.5, a good comparison EUI for typical practice in 1986 for an Energy Edge comparison building might be an LPD of 1.8 W/ft^2 with an EUI of about 5 to 6 kWh/ft^{2}year. This also suggests that energy savings from the lighting measures are probably greater than what the Tuned models indicate if the baseline were common practice rather than MCS compliance.

---

[5] Eastgate had an LPD of 0.9 W/ft^2 and consumed 2.7 kWh/ft^{2}year, which would place it just above the 30% on-time line.

Shell Characteristics and HVAC Energy Use

Evaluating HVAC energy use is more complex than lighting because of variations in factors such as HVAC equipment type, shell characteristics, climate, and occupancy schedules. Table 2.6 shows average HVAC end-use data for the seven Tuned small Energy Edge offices and comparison buildings, plus heating and cooling degree days, and shell characteristics[6].

To examine how shell characteristics vary with climate we plotted the UA_s/A_f vs. heating degree days (Figure 2.6). The UA_s is the total UA of the walls, roof, and glazing (not including floor U). The UA_s/A_f is normalized by the floor area: A_s is the shell area; A_f is the floor area. Similar to the LPD plots, the figure shows that the UA_s/A_f values are lower for Energy Edge small offices than for the ELCAP buildings. The Energy Edge building UA_s/A_f values vary slightly by climate, although the sample size is too small to make generalizations[7].

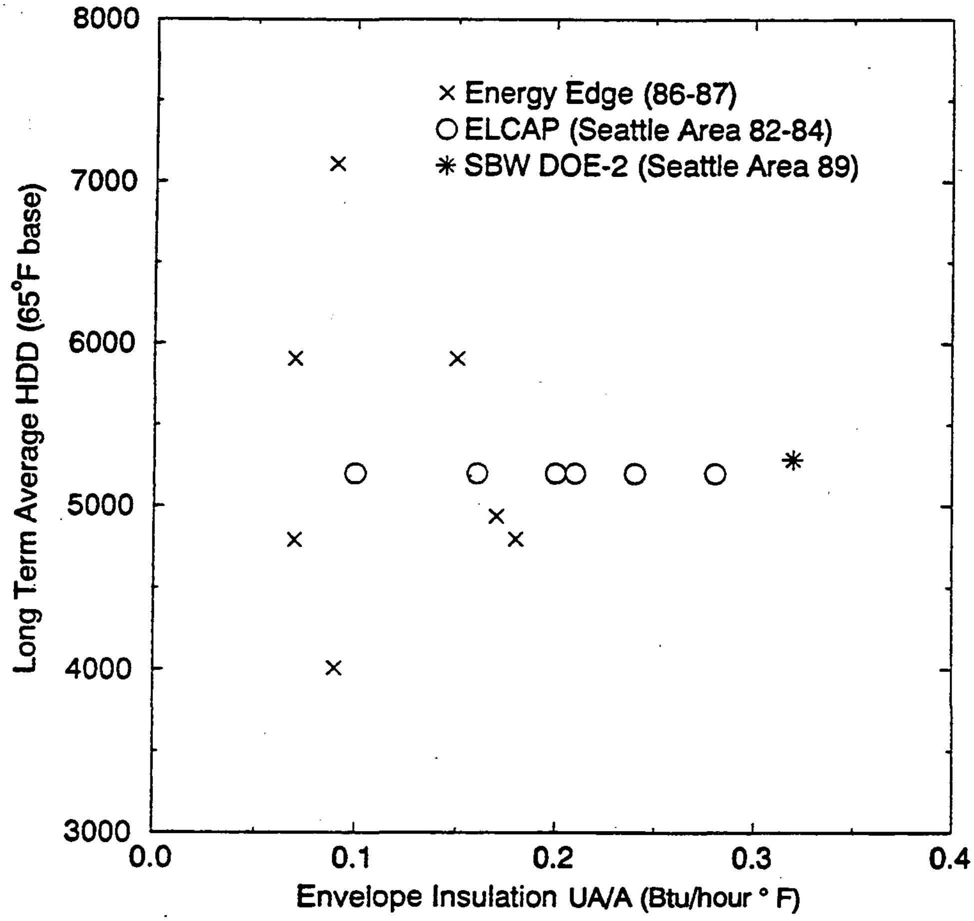


Figure 2.6 Heating Degree Days vs Envelope Characteristics. UA_s/A_f for Small Offices

A recent code compliance study showed current practice had higher levels of insulation than the SBW prototype, with median UA_s/A_f of 0.17 for small offices in Washington (n=13) and 0.23 in Oregon (n=10). As mentioned, the UA_s/A_f values plotted in Figures 2.6 through 2.8 do not include floor area U values. However, the UA_s/A_f values from the code compliance study do. The Energy Edge U values are

---

[6] The table is repeated in Appendix A2 with complete data on individual Energy Edge and ELCAP buildings. Heating typically accounted for almost half of total HVAC energy use, and was the largest end use for all of the small Energy Edge offices except STS.

[7] The SBW UA_s/A_f appears high for 1989 practice, and is higher than the ELCAP values. The two points in the more mild climates (below 5000 HDD) with UA_s/A_f values less than 0.10 are buildings with electric-resistance heat, for which more insulation is often justified and required by code. These two buildings (Landmark and Dubal Beck) are also 2-story buildings (as is East Idaho), which might drive down the UA_s/A_f value because of the ratio of insulated roof to total floor space is higher.

lower than the other buildings listed in Table 2.6, which also includes the baseline U values for the Energy Edge Tuned MCS Base buildings. Wall and glazing U values are similar to new 1990 small offices, but the roof U values from new practice (U= 0.04 and 0.06 for Oregon and Washington) appear lower than the average Energy Edge Base MCS roof U (0.07).

Figure 2.7 shows that, for this sample of buildings, heating energy use tends to increase with higher values of UA_s/A_f, as one might expect from engineering principles. There appears to be lower heating energy use for Energy Edge and comparison buildings with heat pumps compared to buildings with electric-resistance heat[8].

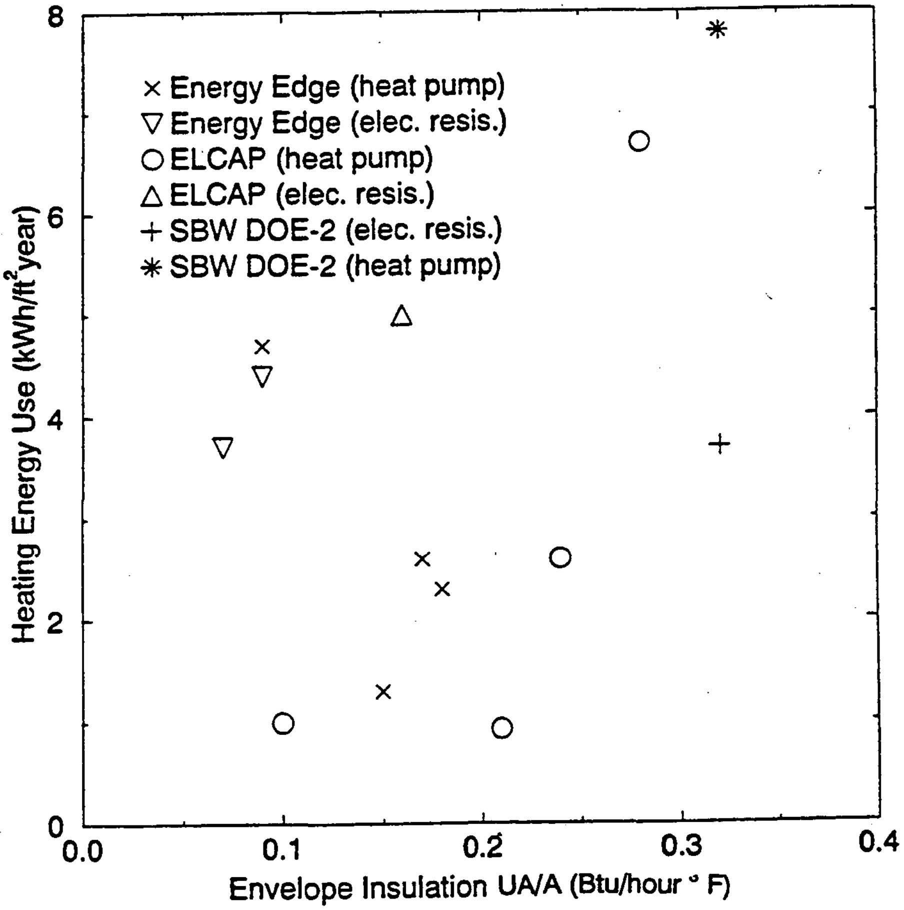


Figure 2.7 Heating Energy Use for Energy Edge Small Offices and Comparison Buildings vs. Envelope Thermal Characteristics. The SBW heating EUIs are high compared with the ELCAP and Energy Edge heating EUIs, probably because of low insulation levels.

Figure 2.8 shows heating energy use versus the UA_s/A_f vs. for six offices; both the Tuned Energy Edge and the Tuned MCS Base values are shown. All of the buildings show similar reductions in heating energy for the change in UA_s (i.e., similar slope), except Hollywood where results from the Tuned model produced negative energy savings for the ground-source heat pump. The comparison of the heating vs. UA_s slopes illustrates that the Tuned Base heating EUI at Hollywood is anomalous and appears to be an unreasonably low Base (further discussed in Chapters 3 and 5). That is, the Tuned Base heating EUI at Hollywood is less than 50% of the Base heating EUIs for the other offices, suggesting it is low[9].

---

[8] Two exceptions are East Idaho (a two-story building) and one ELCAP building. East Idaho's high heating EUI relative to the UA_s/A_f is explained by the cold climate (7110 heating degree days, base 65°F). It is unclear why the ELCAP building used 6.7 kWh/ft²year in the Seattle area with a heat pump.

[9] One difficulty modeling heat pumps was the uncertainty of how to incorporate back-up electric resistance heat that would have been used with a conventional baseline air-to-air heat pumps. It is likely that the use of resistance heat has been underestimated.

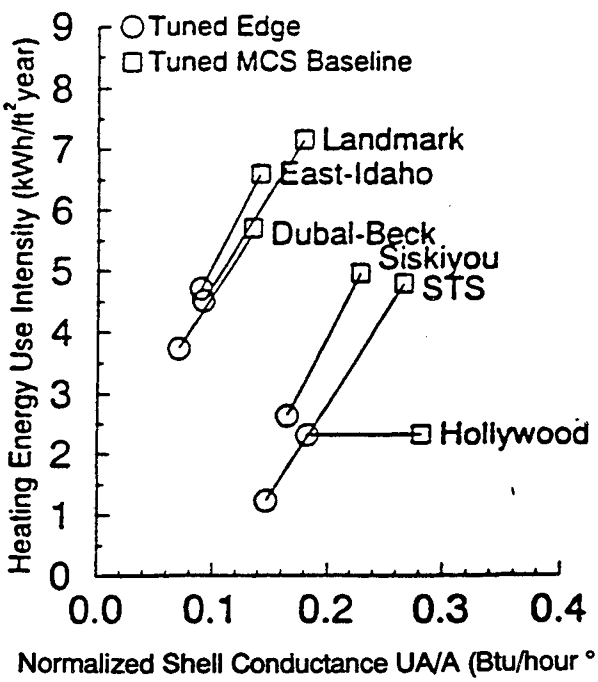


Figure 2.8 Heating Energy Use vs Envelope UA_s/A_f for Tuned Energy Edge and MCS Bases for Small Offices.

Table 2.6. Shell, HVAC, and Climate Data for Energy Edge and Comparison Small Offices.

	UA_s/A_f	Shell Conductance			Degree Days[a]		Heat	Cool	Vent &	Total
		Wall	Roof	Glaze	HDD	CDD			Pumps	HVAC
Sample		U	U	U	(65°F)		(kWh/ft^{2}year)			
ELCAP Avg. (n=7)[b]		0.08	0.04	0.67	5200	129	3.2	2.2	3.0	8.5
SBW DOE-2 (Seattle)										
'89 Practice, Resistance heat	0.32	0.14	0.07	0.72	5290	104	7.8	1.5	2.0	11.3
'89 Practice Air heat pump	0.32	0.14	0.07	0.72	5290	100	3.7	1.5	2.0	7.2
NWPPC Resistance heat	na	na	na	na	5290	100	5.9	3.0	3.9	12.8
Energy Edge Tuned Average (n=7)	0.12	0.06	0.03	0.35	5350	440	3.2	1.1	1.9	5.8
MCS Tuned Base Average (n=7)	0.19	0.09	0.07	0.63	5350	440	5.3	1.3	1.7	7.6
Code Compliance Median										
Washington (n=13)		0.07	0.04	0.50						
Oregon (n=10)		0.10	0.06	0.70						

Building specific data for ELCAP and Energy Edge buildings are listed in Appendix A2 (HVAC components do not sum to total because component data were not available for one building.)

na - not available

[a] Heating and cooling degree days (HDD and CDD) are long-term averages.

[b] ELCAP data are from 1987 or 1988.

UA_s/A_f includes the *shell* UA_s (Btu/hr-°F) from roof, walls, and windows normalized by building *floor* area. Note that floor conductance and infiltration are not included.

Other Energy Use

As shown in Figure 2.4, the Energy Edge small offices not only use less HVAC and Lighting energy than the comparison buildings, they also consumed less Other energy. Table 2.7 shows Other EUIs disaggregated by water heating, exterior lighting, plug loads (e.g., office equipment, coffee pots, and task lighting), and vertical transport. Predicted and actual Other end-use data are shown. The sample sizes for the different sub-categories differ for the Design-phase predicted EUIs because of the lack of detail on the assumptions in the predictions. It may be coincidental that the predicted Other EUI is so close to actual.

Average Design-phase predicted and actual water heating energy use in the Energy Edge small offices is similar to the ELCAP offices. The Energy Edge buildings consume about half as much in plug loads as the ELCAP average and the SBW prototype, but it is unclear why this is the case. The Energy Edge small offices tended to use less energy for exterior lighting as well, as described in Appendix A2.

Table 2.7. Other Energy Use from Energy Edge and Comparison Small Offices.

End-Use Category	**Average Energy Edge**				**NWPPC**	**ELCAP**	**SBW**
	Predicted (kWh/ft²year)	(n)	**Actual** (kWh/ft²year)	(n)		**post-80** (kWh/ft²year)	**'89**
Water Heating	0.52	3	0.53	6	0.3	0.6	0.5
Exterior Lighting	0.55	1	0.64	7	na	1.4	1.3
Plug Loads	1.48	3	1.54	7	3.3	3.0	3.3
Subtotal	2.55		2.71	7	3.6	5.0	5.1
Vertical Transport	na		na		na	0.1	0.3
Total Other	2.43	7	2.63	7	3.6	5.1	5.4

See Appendix A2 for further notes on this table.

Defining a Common Practice Baseline

As discussed in Chapter 1, we have developed a single Comparison buildings EUI to derive an estimate of energy savings based on what might have been built without the Energy Edge program. These are based on engineering judgement from the available new commercial construction data. Based on the above discussion, we estimate that a typical small office built in 1986 or 1987 would use about 19 kWh/ft²year. This total consists of 5.5 kWh/ft²year for Lighting, 10 kWh/ft²year for HVAC, and 3.5 kWh/ft²year for Other energy use. The Other end-use is lower than that for the other comparison buildings, reflecting the lower plug load consumption found in the Energy Edge buildings (for which we assign no credit to the program). Energy savings derived from this common practice EUI are described in Section 1.4 for the net savings analysis.

2.4 Comparing Other Energy Edge Buildings with Regional Buildings

This section describes how the other Energy Edge buildings compare to other regional buildings. The Comparison EUIs used in Chapter 1 for the net savings analysis are developed.

Schools

There are two schools in Energy Edge: Marsing and Edgerton. Total energy use at Marsing was similar to Design-phase predicted, but the end-use distribution is different. Heating is the largest end use, six times greater than predicted. Cooling, Lighting, and Other end uses were less than predicted. As Figure 2.9 shows, the Tuned Base building consumed more energy than the Design-phase predicted Base (with seven times more heating energy). Based on the comparison buildings data, Marsing consumes slightly more than half as much as other new schools. Marsing is the only Energy Edge building that met both project objectives with (1) levelized costs of the package of measures below 56 mills/kWh, and (2) saving more than 30% of the MCS Base EUI.

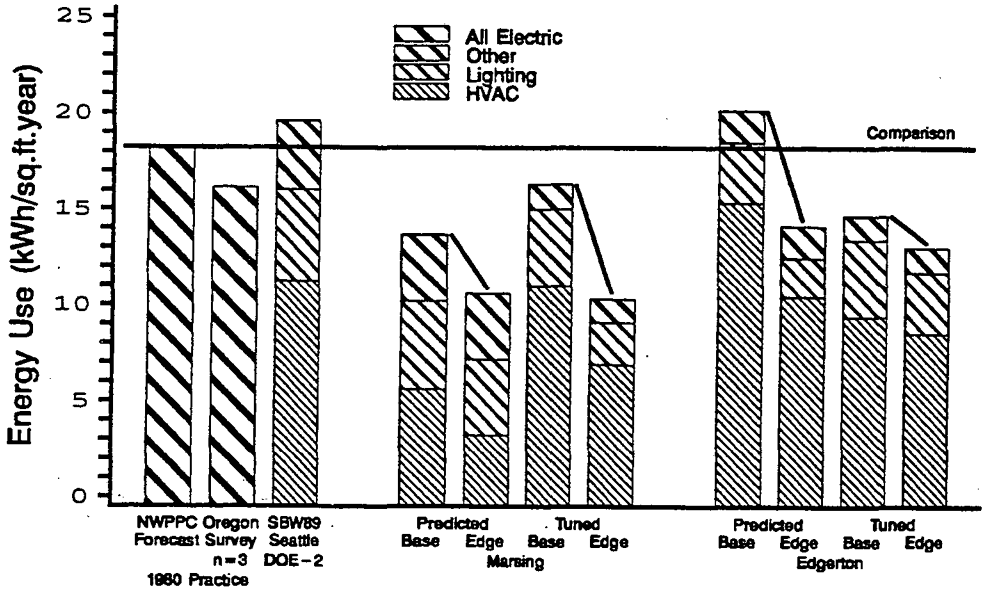


Figure 2.9 End-Use Energy Consumption for Two Energy Edge Schools and Comparison Buildings. The horizontal line at 18 kWh/ft^2-year shows the energy use estimate for a typical comparison building used to derive net energy savings described in Chapter 1.

Edgerton is also heating dominated with no cooling system. HVAC was less than Design-phase predicted and lighting was greater. As shown in Figure 2.9, the Tuned Base consumed considerably less energy than the Design-phase predicted Base. One reason for this change is differences in modeling of the Base HVAC system. The building has a variable-air-volume system which was designed to be more energy conserving than the Base two-pipe fan-coil system. In the Tuned model the VAV was found to use more energy than the fan-coil system.

Another unique characteristic of the schools is that both Tuned MCS Base buildings were modeled with single-paned glazing. Single-paned windows are probably not common practice, especially in Montana, where double-paned windows would be expected. Edgerton uses slightly more energy than Marsing; it is not cooled but is in a colder climate. Both Marsing and Edgerton use far less energy than most new schools. Had the Base buildings used double-paned windows, energy savings for the window measures would be lower because of lower baseline heating energy.

Figure 2.9 shows three sources of comparison data for schools: the NWPPC forecast is for 1990 practice; the Oregon survey represents three schools built in 1980 (NWPPC, 1991); and the SBW prototype is for 1989 practice in a Seattle climate. The SBW prototype includes a heat pump, partial use in the summer, and double-paned windows. Based on these comparison data an estimate for whole-building energy use for schools built in 1986 or 1987 is 18 kWh/ft^{2}year, shown in the figure.

Grocery Stores

There are two grocery stores in Energy Edge: Thriftway, a full-size supermarket, and Tieton, a small convenience center. Tieton consumed less energy than Design-phase predicted, and the Tuned Base was also far lower than the Design-phase predicted Base. Other (primarily cooking and refrigeration) and Lighting end uses were less than predicted, while HVAC energy use was nearly the same as Design-phase predicted. There were many changes between the predicted and Tuned models. The Design-phase predictions assumed there was heat recovery within the refrigeration system for space heat; the Tuned model did not. There was no gas cooking in the Design-phase prediction, but there was in the actual building (and the Tuned model). Another difference is that the Design-phase prediction assumed that the building operated for 24 hours a day, but the actual building operated 16 hours/day. Another difference is the predicted Base assumed a lighting power density of 3.5 W/ft^2 and the Tuned Base was only 1.5 W/ft^2.

Thriftway consumed slightly more energy than Design-phase predicted; while Tuned HVAC energy was nearly twice Design-phase predicted, Lighting and Other EUIs matched closely. Heating and cooling, though minor end-uses, were nearly an order of magnitude greater than predicted. The Tuned Base EUI was less than Design-phase predicted, with less refrigeration energy. This grocery also uses a small amount of gas for cooking. Several measures were dropped from the Tuned model at Thriftway, including the efficient fan motors, partially operating occupancy sensors, malfunctioning anti-condensate heaters, and an ineffective lighting timeclock controller. Thriftway also has a building shell that does not comply with the MCS code because there is no insulation in the floor. Overall, the building uses less energy than typical new grocery stores. The Tuned Base EUI is similar to other comparison EUIs, which suggests that the energy savings estimates from the Tuned model are probably a good indication of savings for the strategies employed.

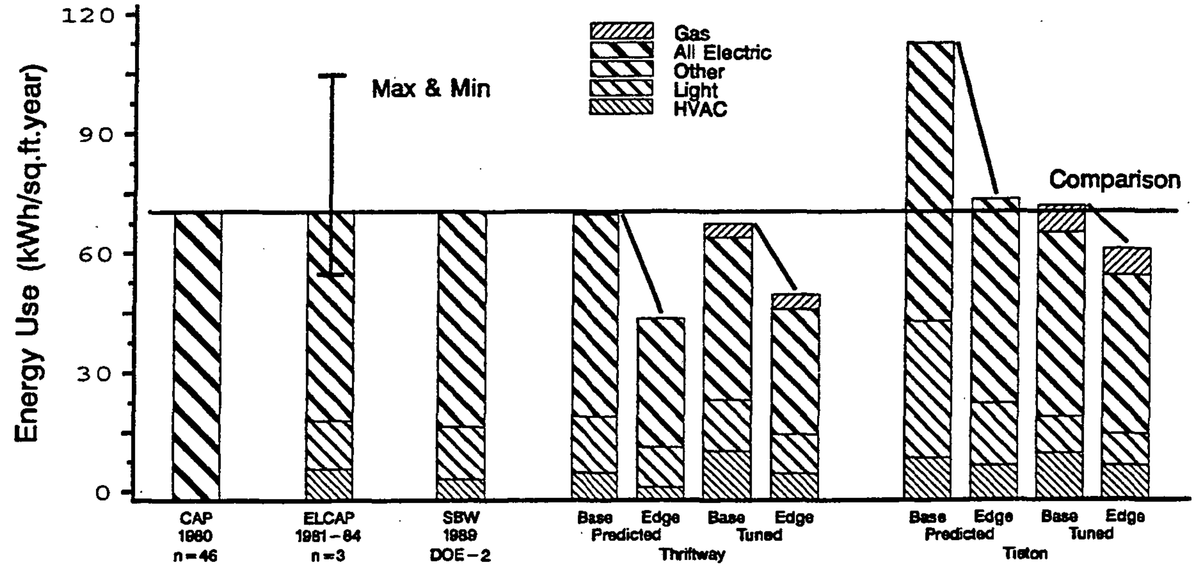


Figure 2.10 End-Use Energy Consumption for Two Energy Edge Groceries and Comparison Buildings. The horizontal line at 70 kWh/ft^2-year shows the energy use estimate for a typical comparison building used to derive net energy savings described in Chapter 1. Gas is shown in kWh/ft^{2}year, converted at 3412 Btu/kWh.

Figure 2.10 shows three comparison EUIs. The Commercial Audit Program (CAP) surveyed 46 groceries for an estimate of 1980 practice (NWPPC, 1991). The ELCAP average (and range) is based on three groceries built between 1981 and 1983 (a 3 kft^2 deli-grocery, a 22 kft^2 grocery, and a 1 kft^2 grocery store located within a larger building). The SBW 1989 prototype is a full-size grocery with many features found in Thriftway. The three comparison sources show similar EUIs of 70 kWh/ft^{2}year, which are nearly identical to the predicted Base EUI for Thriftway and the Tuned Base for Tieton. This does not include the gas use for cooking found in both Energy Edge groceries.

Fast-Food Restaurants

There are three fast-food restaurants in Energy Edge: McDonald's, Burger King, and Skippers. McDonald's was evaluated with a MCT model, Burger King was Tuned to whole-building utility bills (i.e., without monitored end uses), and Skippers has not been tuned.

McDonald's, as an all-electric restaurant, has high cooking and refrigeration energy use, with ventilation as the next largest end use. Overall, the building used less energy than Design-phase predicted, with much less cooking and refrigeration, but more ventilation and exterior lighting. The measures saved more energy than predicted, with lighting saving more than twice Design-phase predicted. The energy savings, however, is due to a change in the Base lighting for the kitchen, which was much higher than common practice in the Tuned model Base (over 5 W/ft^2). The Base kitchen lighting at Burger King was estimated at 2.2 W/ft^2, which is similar to the 2.0 W/ft^2 assumed by SBW in the fast-food prototype for 1989 practice. Further analysis of common practice trends are needed to identify the appropriate baseline.

Compared with the CAP survey results and the SBW 1989 prototype, McDonald's consumes about as much as similar new fast-food restaurants. Total electricity use at McDonald's is similar to electricity use at Burger King, but Burger King uses an additional 255 kBtu/ft^{2}year of gas for cooking. The end-use data for Burger King are estimated with DOE-2. The building consumed more electricity, but less gas, than Design-phase predicted. Burger King uses more heating energy than McDonald's, suggesting that the exhaust heat recovery has been an effective measure at McDonald's.

Skippers was predicted to use 36 kWh/ft^{2}year of electricity plus gas. Electricity and gas consumption are significantly greater than Design-phase predicted. However, the predicted EUI for Skippers was far lower than the other two fast-food restaurants and the comparison EUIs.

Figure 2.11 shows the end-use data for the MCS Base and Energy Edge restaurants and two comparison EUIs. The CAP 1980 practice EUI of 141 kWh/ft^{2}year is an average from 16 fast-food restaurants. The SBW 1989 prototype consuming 123 kWh/ft^{2}year is for an all-electric fast-food restaurant with almost half of the total (57 kWh/ft^{2}year) for cooking. Based on these two comparison EUIs, we estimate a common practice EUI for the mid-1980s at 130 kWh/ft^{2}year.

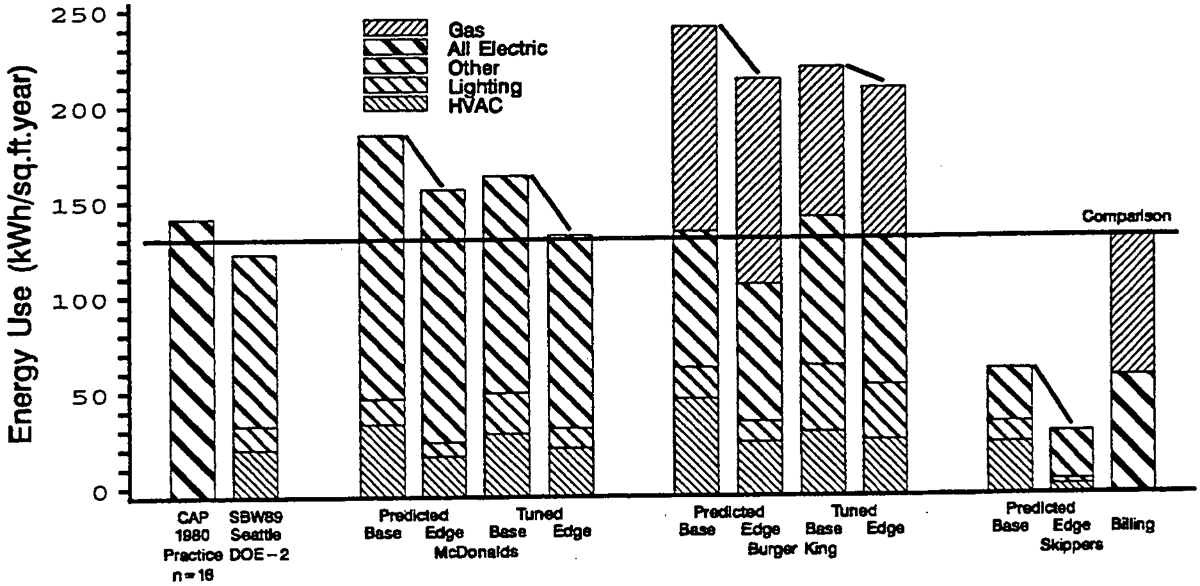


Figure 2.11 End-Use Energy Consumption for Three Energy Edge Fast-Food Restaurants and Comparison Buildings. The horizontal line at 130 kWh/ft^2-year shows the energy use estimate for a typical comparison building used to derive net energy savings described in Chapter 1.

Retail

Retail buildings are the second largest commercial subsector using 18% of regional commercial sector electricity (NWPPC, 1991; office buildings are the largest subsector, consuming 28%). There is only one retail building in Energy Edge: Evergreen, a strip-retail establishment. Both Lighting and HVAC were greater than predicted at Evergreen, while the sum of the Other end uses was about equal to the Design-phase prediction. It is a heating-dominated building, consuming six times more heating (and less cooling) than predicted.

Figure 2.12 shows three sets of retail comparison data. The first two are SBW 1989 prototypes for small (13 kft^2) and large (120 kft^2) retail establishments. The third is a NWPPC forecast estimate for 1990 practice. We have not included the four new ELCAP retail averages because the buildings were small and two of the four were part of larger buildings. Given these comparisons, we estimate that an average retail establishments built in the mid-1980s probably used about 18 kWh/ft^{2}year.

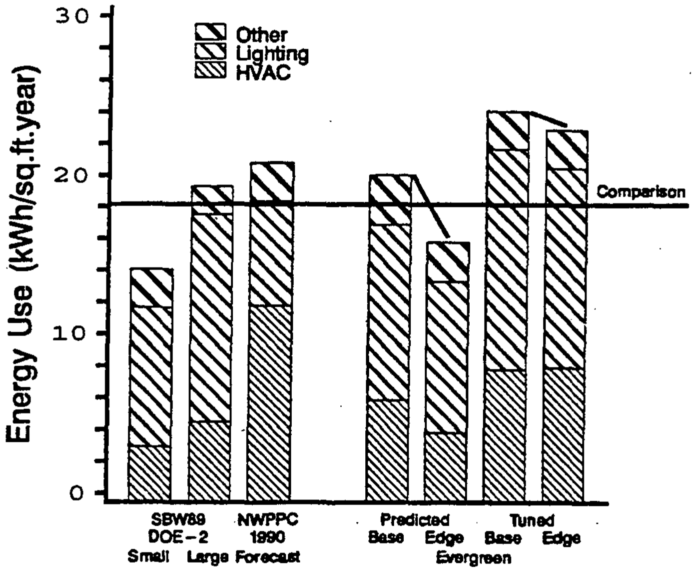


Figure 2.12 End-Use Energy Consumption for One Energy Edge Retail Building and Comparison Buildings. The horizontal line at 18 kWh/ft^2-year shows the energy use estimate for a typical comparison building used to derive net energy savings described in Chapter 1.

Large Office Buildings

Large office buildings are greater than 20 kft^2, of which there are seven in Energy Edge. Four of the seven have been evaluated with Tuned models. As shown in Figure 2.13, one building, Eastgate, consumed more than twice as much energy as Design-phase predicted, with heating energy use three times greater than predicted. Eastgate is one of the three offices for which the Other end use exceeded Lighting (East Idaho and West Yakima are the others).

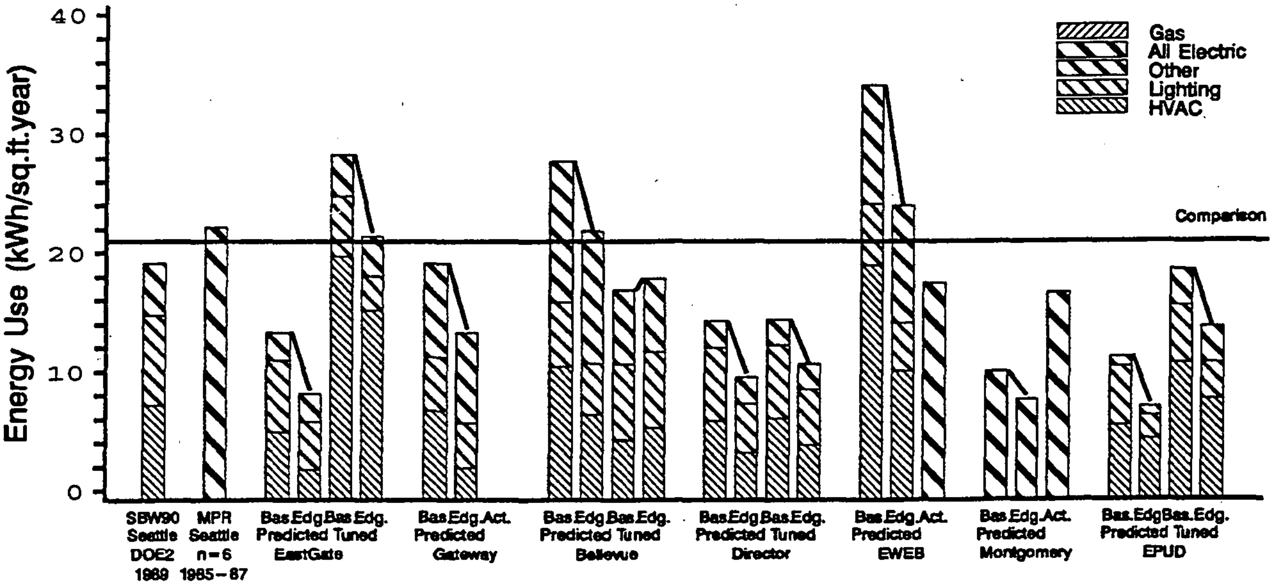


Figure 2.13 End-Use Energy Estimates and Whole-Building Energy Use for Energy Edge Large Offices and Comparison Buildings. The horizontal line at 21 kWh/ft^2-year shows the energy use estimate for a typical comparison building used to derive net energy savings described in Chapter 1.

The EUI at Eastgate is higher than all of the other Energy Edge small and large offices. Ironically, however, unlike many of the other offices, the measures were found to be highly cost-effective. The strong economic performance of the efficiency measures illustrate some conceptual issues with measure vs. whole-building evaluation techniques. The package of measures met the levelized cost criteria (less than 56 mills/kWh), but these results stand in contrast to the high whole-building energy use. The building has the highest EUI of all the Tuned offices, with monitored consumption of 17 kWh/ft^{2}year and 20 kWh/ft^{2}year in the Tuned model with TMY weather. The Tuned Base building energy use is 26 kWh/ft^{2}year, which is almost twice the average Tuned Base EUI for the seven small offices (14 kWh/ft^{2}year). Three reasons for high energy use are the use of electric-resistance heat, irregular use of night-setback, and low shell insulation levels. Technically, the envelope complies with code, but is probably below common practice.

One interesting finding among the large offices is that the range in actual energy use among the six buildings is smaller than that of the Design-phase predicted Energy Edge EUIs (we also found this with the small offices). This finding suggests that the predictions should have been compared against regional averages to assess if there were outliers due to erroneous assumptions in the Design-phase predictions.

Two comparison EUIs are shown in Figure 2.13. First, is the SBW 1989 prototype based on a 408 kft^{2}year building. Second, is the MPR average for six large offices built in 1986 and 1987, an excellent comparison group for Energy Edge large offices because they were built a year or two before the Energy Edge offices. Based on these two sources we estimate that a typical large office built in the mid-1980s consumes about 21 kWh/ft^{2}year.

Miscellaneous Buildings

There are five buildings categorized as miscellaneous buildings, as shown in Figure 2.14. None of the five have post-occupancy Tuned models. Four of the five buildings consume more than twice as much energy as predicted. It is likely that modeling practices for miscellaneous building types are less well-defined than for other more common types of buildings, which contributed to the under-predictions. We have not compiled comparison data for the miscellaneous buildings because of the lack of data available for these less-common building types. We provide some comments on the performance of the measures and total energy use trends.

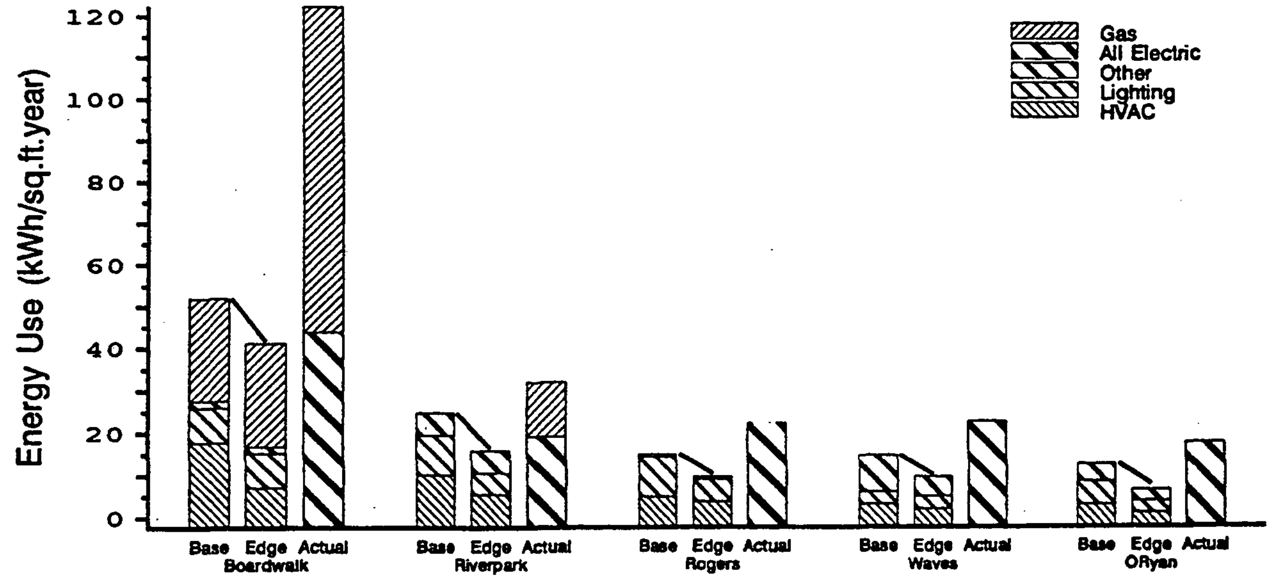


Figure 2.14 End-Use Energy Estimates and Whole-Building Energy Use for Miscellaneous Energy Edge Buildings.

Boardwalk, which houses a restaurant and an office, consumes more than twice as much energy as Design-phase predicted. There were problems with a few of the efficiency measures. The air-to-air heat exchanger in the restaurant and lounge was not being used because high volumes of low-temperature air caused comfort problems. Also, early in the building's history the water pump for the water-source heat pump system malfunctioned.

O'Ryan, a light industrial building, also consumed more than twice the Design-phase predicted energy use. Several measures changed from the prediction. For example, 40W and 34W T-12 lamps were installed in place of the prescribed 32 Watt Octron lamps. Roof insulation was increased from R-11 to R-19. Comfort problems resulted in occupants bringing in portable space heaters. Night setback control was erratic and often overriden.

Riverpark, a nursing home, used about 15% more electricity than Design-phase predicted. The original design was based on double occupancy rooms, but a number of the rooms have single occupancy. The building is occupied 24-hours per day, using natural gas for hot water, cooking, and laundry. Early problems with the cooling and heat-recovery systems have been repaired.

Roger's consumed about twice as much as Design-phase predicted. Some of the difference is related to changes from the design. The showroom has single- instead of double-paned glazing. There is no night setback or timeclock control for the heat pumps. Magnetic ballasts were installed in many of the fixtures instead of the electronic ballasts. Metal halide fixtures (400 W each) were installed in the shop instead of fluorescent fixtures. Several wall areas received less than the R-22 insulation specified in the design.

Waves, a small hotel on the coast, also consumed about twice as much as predicted. Infiltration tests in 1987 showed that the building was tighter than average small hotels. The second-story daylighting was reported to be successful, with lights rarely on during daylight hours. Heating is provided by electric-resistance wall heaters and infrared heat lamps in bathrooms. The electric water heater was supplemented with flat-plate solar collectors.

2.5 Occupant Satisfaction with the Building Performance

In consideration of the broad perspectives of the Energy Edge evaluation it is important to demonstrate that the buildings have low-energy use, plus meet the expectations of the users and owners for their functional, aesthetic, and ambient features. The final reports from the research team at the University of Washington (Heerwagen et al., Aug. 1991 and Heerwagen et al., Oct. 1991) documented high overall occupant satisfaction with the Energy Edge Buildings. Their survey of 264 occupants in seven of the Energy Edge office buildings found a high level of user satisfaction with the workspaces and with the aesthetic and functional aspects of the buildings. This finding, the report notes, underscores the idea that buildings can be energy efficient without of user amenity.

Despite high levels of satisfaction overall with the lighting, there were lighting problems in all seven buildings. Lighting was frequently judged too bright for some tasks and too dim for others. Several workers noted problems with glare and reflections on their computer screens. The daylight controls were another source of occupant dissatisfaction, often because the stepped dimming was too abrupt or because the daylighting levels were too low.

Thermal dissatisfaction varied across buildings, with typical complaints being spaces too cold on winter mornings and too warm on sunny afternoons. Occupants tended to rate air quality quite high. Many workers mentioned acoustic problems as their principal source of discomfort. Noise distraction from conversations, telephones, equipment was prevalent across buildings. This finding points out the potential conflict in designing large open offices for daylighting and passive solar and the need for acoustic privacy.

While occupant satisfaction was high overall, occupants did not necessarily passively accept what was provided for them. Many occupants added desk lamps, fans, and electric space heaters to make their workspaces more comfortable. Others removed ceiling lights and covered up daylight sensors to improve lighting conditions. The high degree of occupant changes suggests that building designers and engineers should: a) provide greater opportunities for occupants to control conditions in their workspaces (buildings that had the greatest opportunity for occupants to control thermostats also had the highest thermal satisfaction ratings); and b) increase the variability of interior conditions to better match the range of human environmental needs.

Ideally we would compare the level of satisfaction found in the Energy Edge buildings with results from studies of similar buildings. Unfortunately we do not have such a sample of comparison buildings. However, the general assumption is that they are similar to other new buildings, with no outstanding set of problems identified. Most buildings have air flow and temperature control problems in particular zones or spaces. A study of the environmental conditions in 10 office buildings in Northern California found, for example, that satisfaction with their thermal environment was lower than non-thermal aspects of the work area (Schiller and Arens, 1988). The study noted that there appeared to be air flow problems in most buildings.

Chapter 3. Measure Energy Savings and Cost Effectiveness

Key Findings from This Chapter

- On average, Tuned energy savings for individual measures were 20% less than Design-phase predicted energy savings.
- Among the 78 measures with energy savings estimates and complete cost data from the Tuned models, 41% met the cost-effectiveness criterion (CCE of 5.6 ¢/kWh).
- Among the general classes of measures, the refrigeration and miscellaneous measures were the most cost-effective with median CCEs of 5.4 and 1.6 ¢/kWh, respectively. Lighting measures were the next most cost-effective at 7.5 ¢/kWh (median), followed by shell measures at 7.8 ¢/kWh. The HVAC measures were the least cost-effective, with median savings of 12.7 ¢/kWh.
- The most important reason energy savings were not as great as predicted is because of changes in measure characteristics, such as different baseline R-values or higher lighting power densities. The second most important reason was problems with control functions from poor commissioning and O&M, such as poor calibration of occupancy and daylighting sensors or economizer damper problems.

3.0 Introduction

This chapter discusses the energy savings and cost effectiveness of individual energy-efficiency measures. The Energy Edge data set contains information on over 200 individual measures among the 28 buildings. Our ability to analyze the cost-effectiveness of these measures depends upon the extent to which reliable information about dollar costs and energy savings is available.

The chapter is divided into three sections. The first section discusses the measure cost data, reviewing costs from the predictions, reported costs from invoices, and standard costs developed to improve consistency among the data definitions. The efforts within the project to develop reliable incremental measure cost data have been significant, though not as intensive as the efforts to estimate energy savings. The second section discusses the energy savings and cost effectiveness results of individual measures from the Tuned models. These results are compared with the predicted measure performance. The complete set of Design-phase predicted and Tuned energy savings and the cost data for each measure are presented in Appendix A3. The final section summarizes results from previous analyses of individual measures focusing on occupancy sensors, heat pumps, and economizers. This analysis is based on the results of the Tuned models supplemented with data from the audits and hourly end-use monitoring.

3.1 Measure Cost Data

Cost Components

Determining the total cost of efficiency improvements is a difficult task because it involves many kinds of costs and changing construction practice. Selecting which measures to install generates administrative, design, and modeling costs. Installing the selected measures incurs additional design and construction expenses. Gathering information about the measure installation, implementation, and operation requires further expenditures. The Energy Edge cost-effectiveness analysis focused on tracking the design and construction costs for implementing the individual measures within each building. Each measure has a set of construction and design costs for the Base building and a similar set for the Edge design. Construction costs include materials and labor. Design costs estimate additional engineering effort. The differences between these sets of costs provide incremental costs for each measure, which, when summed, indicate how much more expensive each Energy Edge building is relative to its Base.

Costs unallocated to specific measures included administrative, design, modeling, and reporting expenses, which range from zero to as much as 40% of the total costs (measure-specific plus unallocated) per building (Table D.3, Harris et al., May 1990). Across all buildings, unallocated costs represent about 5% of the total $5 million estimated costs of energy-saving features, or $250,000. The data are problematic because of inconsistent treatment of these costs. Unallocated costs were not included in the Energy Edge cost-effectiveness analysis[1].

---

[1] Although program delivery costs were assumed in the net program savings analysis in Chapter 1.

Predicted, Reported, and Standard Cost Data

Measure costs were originally planned to be compiled and compared in two forms: "Design-phase predictions" and "Reported" costs from construction invoices. Although a significant effort was made to develop reliable incremental measure cost data, inconsistencies in cost accounting and changes in measure characteristics have complicated these comparisons. Reliability issues include:

- Similarities between predicted and reported costs may not reflect accurate estimates as much as unwillingness by program participants to revise estimates from predicted costs.
- There are inconsistencies in measure assumptions, both among buildings and between the predicted and reported conditions of a given measure in a single building.
- The degree of disaggregation for both costs and energy savings, where measures were evaluated as a group in the original approval package, complicate comparisons.
- Inconsistencies in treatment of incremental design costs and other "unallocated" costs are common, which may indicate unfamiliarity with new technology more than the absolute difficulty of a design task (e.g., specifying efficient lights or windows should take no more time than specifying standard ones, but installing an energy management system does require more engineering effort than not installing one).
- There was no treatment of added "O&M" costs (or cost savings), where these are significantly different from the baseline technology.
- There are ambiguities in some of the owner-paid, cost-shared, and BPA-funded measures in accounting for the amenity value of measures such as daylighting or the fire and security benefits of an energy management and control system.
- Indirect effects on costs (even more than on energy) of HVAC downsizing from other load-reducing measures have been difficult to track.

In addition, the predicted and reported costs apply only to a specific measure in a particular building at a given time. To remedy some of the above difficulties and broaden the perspective of the analysis, a third method of analyzing the measure costs was planned. The "Standard" cost analysis was designed to complement the comparison between the predicted and reported costs by addressing expected cost-effectiveness for the same measures implemented in the future, in a typical new building in the region. Standard cost estimates were to be developed to reflect the typical cost of a measure after it has become *familiar* to those who build new commercial buildings in the region. Since many of the Energy Edge measures were relatively new at the time the project began, the standard costs should have accounted for immature market pricing conditions, such as higher production costs, limited production runs, and utility incentive programs. Standard costs were to be used in all of the Tuned models.

Like the planned comparison between predicted and reported costs, these initial objectives were idealistic and quickly met with practical barriers. It was found unfeasible to obtain realistic design costs from contractors for items and systems in a hypothetical project. Contractors contacted for this purpose pointed out that they spend time preparing bids and costs in hope of doing the work, and they would not provide system costs for conceptual analysis. Similarly, there is no incentive for manufacturers' representatives to prepare possible design budgets, unless they feel it likely that their products may be specified on future projects. As a result, standard costs only include construction costs (materials and labor) developed primarily from Means Cost data. Contractor overhead and profit factors were estimated as a fixed percentage (15% to 27% of materials and labor) and do not reflect the intended "familiarity" with efficient technologies. Furthermore, standard costs were used in only 13 of the 18 Tuned models (see Table 1.2).

An important complication to the analysis is the differing levels of aggregation present in the Energy Edge measures. For example, in 12 buildings, wall and roof insulation were sometimes recorded together and sometimes separately. In some cases, only part of a predicted measure was installed or worked. We defined over 40 measure "aggregations", resulting in two overall data sets, an "unaggregated" one and an "aggregated" one.

Status of Cost Database

The measure cost data were compiled in a single database. The database includes twelve values to record design and construction costs for both the Edge and Base buildings at the predicted, reported, and standard stages. These twelve costs were manipulated to produce total and incremental costs at each stage.

Predicted, reported, and standard cost data are not available for all of the buildings and measures. Predicted costs are available for all 28 buildings; only 16 have reported costs. Standard costs were developed for a different 16 buildings (of which nine also have reported costs). Buildings that have reported or standard costs often have them for a different set of measures than predicted. McDonald's, for example, has standard costs only for owner-funded measures, and none of these measures have predicted costs. Some of the discrepancies are from predicted measures that were not installed, or reported measures that were designed and installed after the predicted costs were prepared.

Design costs were not used in the cost-effectiveness analysis because of their unreliability, the lack of data in the standard costs, and their relatively small size in comparison to construction costs. Where figures were given for design costs in the predictions, on average they were 6% of the total design and construction costs. At the reported stage, they rose slightly to 8% of the total, but it was decided that including their cost in the analysis would add more uncertainty than value. As a result, all costs discussed in this report are incremental construction costs, which include labor, materials, and overhead.

Whole-Building Costs

Table 3.1 shows the total predicted, reported, and standard incremental construction costs by building for the BPA-funded measures, normalized by floor area and adjusted to 1991 dollars based on the consumer price index (U.S. Bureau of the Census, 1992). Floor area normalization is most useful for measures that cover a large part of the building (e.g., lighting fixtures), and less so in others, such as where a measure is installed only in a small part of the building (e.g., occupancy sensors).

Table 3.1 Total and Average Incremental Costs for BPA-funded Measures.

	Total Incremental Cost *(1991\$/ft^2)*			
Building	**Predicted**	**Reported**	**Standard**	**Tuned**
Fast Food				
Burger King	2.54	3.18		yes
McDonald's	8.52	7.92	2.62	yes
Skippers	8.38		23.10	
Grocery				
Thriftway	2.30	1.73	2.38	yes
Tieton	9.88	2.94	3.16	yes
Large Office				
Bellevue	1.94		1.98	yes
Director	2.19		3.96	yes
Eastgate	3.95		4.60	yes
EPUD*				yes
EWEB	7.20			
Gateway	2.1			
Montgomery	0.52			
Miscellaneous				
Boardwalk	4.27	6.51		
O'Ryan	2.25		1.73	
Riverpark	2.60		2.90	
Rogers	2.58	5.85		
Waves	3.99			

Table 3.1. Total and Average Incremental Costs for BPA-funded Measures. (cont.)

Building	Total Incremental Cost *(1991$/ft²)* Predicted	Reported	Standard	Tuned
Retail				
Evergreen	1.22		1.32	yes
School				
Edgerton	4.81	8.03	12.88	yes
Marsing	5.13	7.26	11.18	yes
Small Office				
Caddis	4.51	4.69		
Dubal	3.50	3.83		yes
East Idaho	4.34	4.35	5.40	yes
Hollywood	4.95	3.04	3.37	yes
Landmark	3.51	2.99	5.14	yes
Siskiyou	7.84	5.54	1.56	yes
STS	13.33	20.67		yes
West Yakima	2.10	2.10		yes
Average (All)	**4.46**	**5.66**	**5.46**	
Average (n=9)**	**5.70**	**4.87**	**5.30**	

*Measures owner-funded, but included elsewhere as BPA-funded because owner is BPA customer utility.
**Second average is for the 9 buildings which have all three cost estimates.

To compare predicted, reported, and standard costs we need to compare the averages for the nine buildings where all three costs were available. For this subsample predicted costs are highest at 5.70 $/ft², reported costs are lowest at 4.87 $/ft², and standard costs are slightly lower than predicted at 5.3 $/ft². Comparing these three costs can be deceiving, however, because costs at different stages often do not reflect the same set of measures. The predicted costs often include measures that were dropped from the Tuned models (as discussed in Chapter 5).

Among all buildings, STS shows the highest predicted cost (13.33 $/ft², nearly three times greater than the predicted all building average) and an even higher reported cost (20.67 $/ft², about 3.5 times the reported average for all buildings). The high predicted costs are an expensive wall finish. Reported costs were even higher, raised by an increase in the costs for the wall finish and the water-source heat pump. The highest standard costs are at Skippers, where the $23.10/ft² cost is more than four times the average because of an expensive Energy Management and Control System (EMCS). Measure costs per building area were far lower than average for the three largest office buildings: Gateway, Montgomery, and Bellevue.

Costs for Individual measures

To provide additional information on how costs varied among the buildings, measures, and the three categories of costs we present cost data for six measure types that appear in five or more buildings. These measures are: roof insulation; wall insulation; window measures; efficient lamps, ballasts and fixtures; heat pumps; and economizers. For each measure type we present a graph of the range and average for predicted, reported, and standard costs[2].

Among these measures we did not find that standard costs were higher than reported costs. There is considerable variation within measure types and across categories. The measure "wall insulation" for instance, indicates an increase in R-value, but it does not distinguish between an increase from R-5 to R-25 (Design-phase predicted baseline to Energy Edge improvement for Caddis) and an increase from R-11

---

[2] The "All data average" line connects the three average costs for the complete set of data (in which the sample sizes vary). A second line connects the average costs for the sample where all three costs were available, listed as the "Consistent group average".

to R-20 (predicted improvement for East Idaho). It also does not reflect differences between Design-phase predicted, as-built, and Tuned model measures within a building, resulting either from changes in baseline assumptions or alterations to initial Energy Edge designs. The reported wall insulation improvement for Caddis, for example, changes both the predicted and the Energy Edge R-values (reported data indicates R-11 to R-19).

Roof insulation measures were installed in 23 buildings. Data across all cost categories were gathered only for Edgerton (Figure 3.1). The all-data average was 0.66 $/ft^2. The highest cost for roof insulation was 2.62 $/ft^2 predicted for Skipper's restaurant. The standard cost for Skipper's roof insulation was 0.26 $/ft^2, only a tenth of the predicted value.

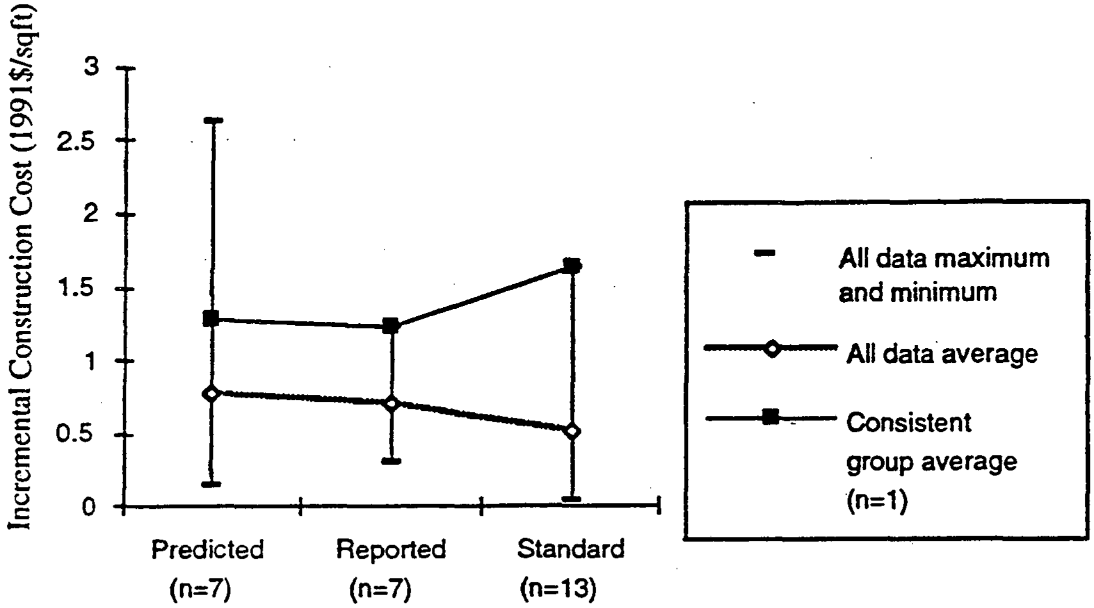


Figure 3.1. Average Predicted, Reported, and Standard costs for Roof Insulation.

Wall insulation measures were installed in 19 buildings. Figure 3.2. shows that the highest cost is the 1.82 $/ft^2 standard cost at Marsing, and the lowest is the 0.04 $/ft^2 cost at Hollywood. The high reported cost of 1.79 $/ft^2 also comes from Marsing, but there were no predicted costs for this measure in this building. Again consistent data for all categories were only gathered for Edgerton. Cost data for this building across cost categories were on the low than half of the all-data average (0.33 $/ft^2).

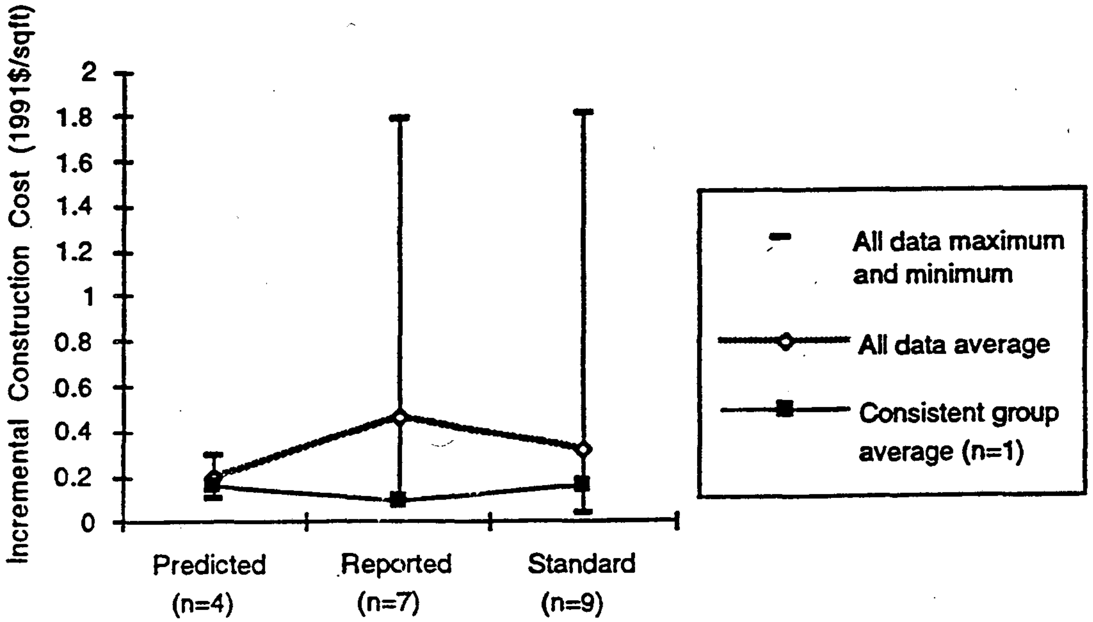


Figure 3.2. Average Predicted, Reported, and Standard costs for Wall Insulation.

Window measures, consisting of low-emissivity coatings, reflective tints, and thermal-break panes, were installed in 25 buildings. Figure 3.3 shows that the greatest expense for window measures was the predicted cost of 2.35 $\$/ft^2$ for the low-emissivity, tinted windows at STS and the lowest costs are the 0.02 $\$/ft^2$ standard cost for tinted windows at Thriftway. Normalizing costs per window area rather than floor area might have reduced the range. The "All-data" and "Consistent group" averages are similar, showing reported and standard costs to be about the same, or slightly lower than predicted costs, at about 0.75 $\$/ft^2$. Costs for low-emissivity glazings, however, have decreased in the 1980s as manufacturing costs were reduced and demand for the product increased. This is the kind of change we expected to account for with the standard cost analysis, but we found little evidence of the change with our limited sample.

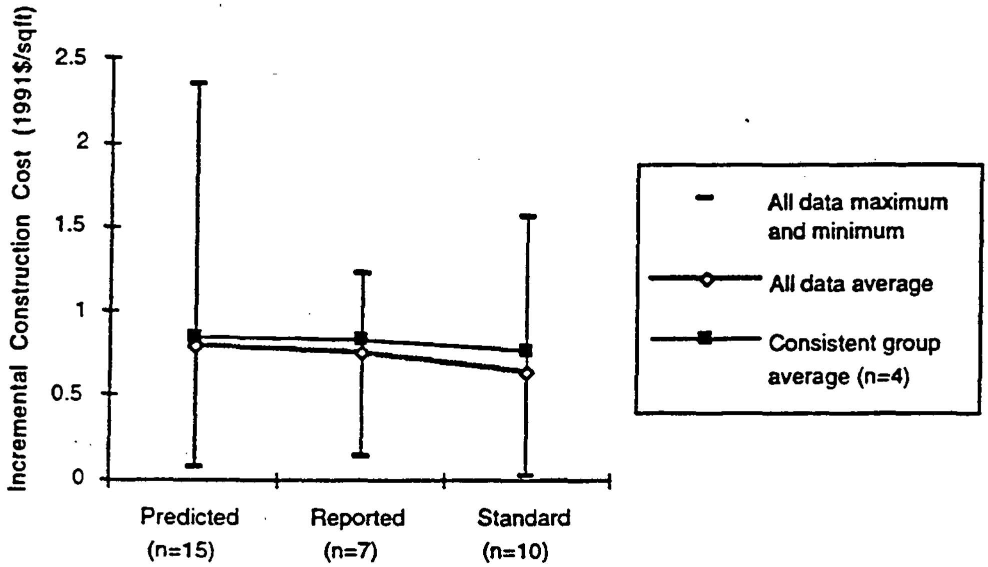


Figure 3.3. Average Predicted, Reported, and Standard costs for Windows.

Efficient lamps, ballasts, and fixtures were installed in 23 buildings. Lighting equipment included in this broad category vary from efficient 32 Watt T-8 octron lamps with solid-state electronic ballasts to now somewhat standard 34 Watt energy-saving lamps with efficient core-coil ballasts. Consistent cost data were available for two buildings. Measure costs ranged from a reported high of 2.46 $\$/ft^2$ at Siskiyou to a standard low of -0.07 $\$/ft^2$ at Tieton. Figure 3.4 shows that reported costs are about 0.20 $\$/ft^2$ higher than predicted, while standard costs are closer to predicted values for both the all-data average and the consistent group average.

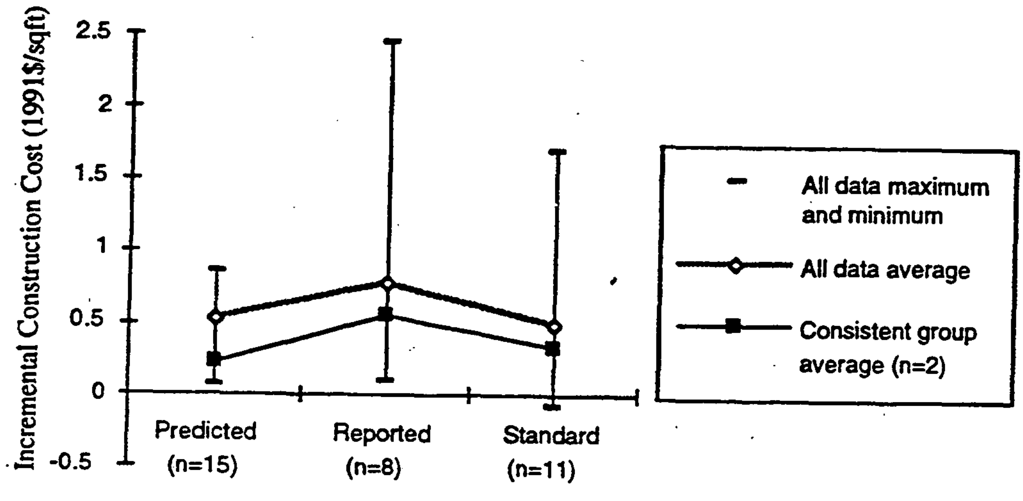


Figure 3.4. Average Predicted, Reported, and Standard costs for Lamps, Ballasts, and Fixtures.

Heat pumps (air- and water-source) were installed in eight buildings. A complete set of data was collected for one building (Marsing). Heat pump costs are the incremental costs for a high COP heat

Heat pumps (air- and water-source) were installed in eight buildings. A complete set of data was collected for one building (Marsing). Heat pump costs are the incremental costs for a high COP heat pump compared to a baseline heat pump with an efficiency required by the MCS code. Figure 3.5 shows that the reported average is 2.66 $/ft^2$, more than twice the 1.25 $/ft^2$ predicted cost for this measure, and the standard average cost (0.81 $/ft^2$) is one-third lower than predicted. The most expensive were the water-source types, responsible for the higher reported cost at STS of 8.32 $/ft^2$ and the 4.41 $/ft^2$ reported cost at Boardwalk.

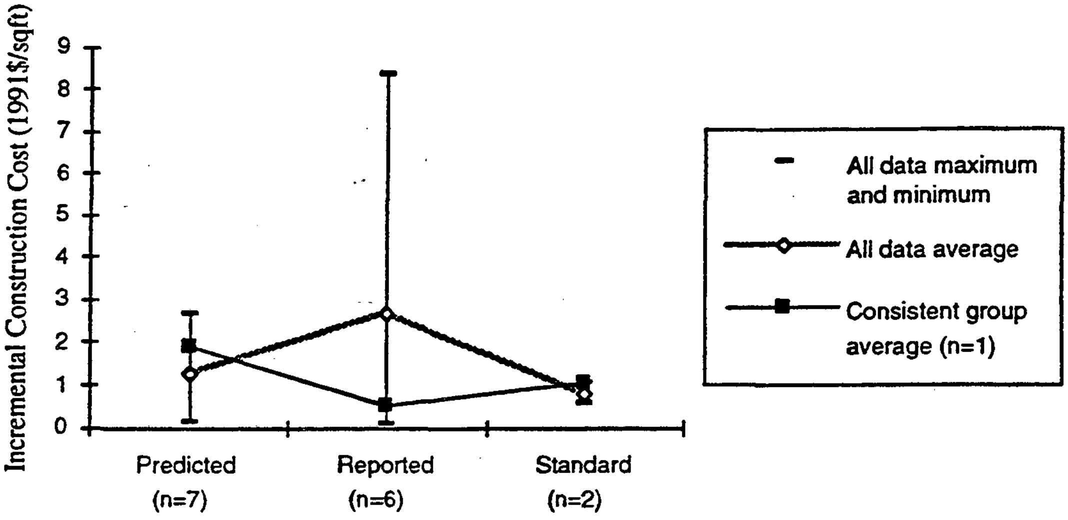


Figure 3.5. Average Predicted, Reported, and Standard costs for Efficient Heat Pumps.

Economizers were installed as efficiency measures in seven buildings. These are economizers in small buildings since they are required by code in larger systems. Figure 3.6 illustrates that this measure ranges from a standard cost low of about 0.16 $/ft^2$ at Hollywood to a standard cost high of 1.53 $/ft^2$ at East Idaho. These two buildings comprise the "consistent group" (having all three kinds of cost data); the average cost of economizers was $0.75/ft^2$, which is slightly higher than the "all-data" (any cost category) average of $0.58/ft^2$.

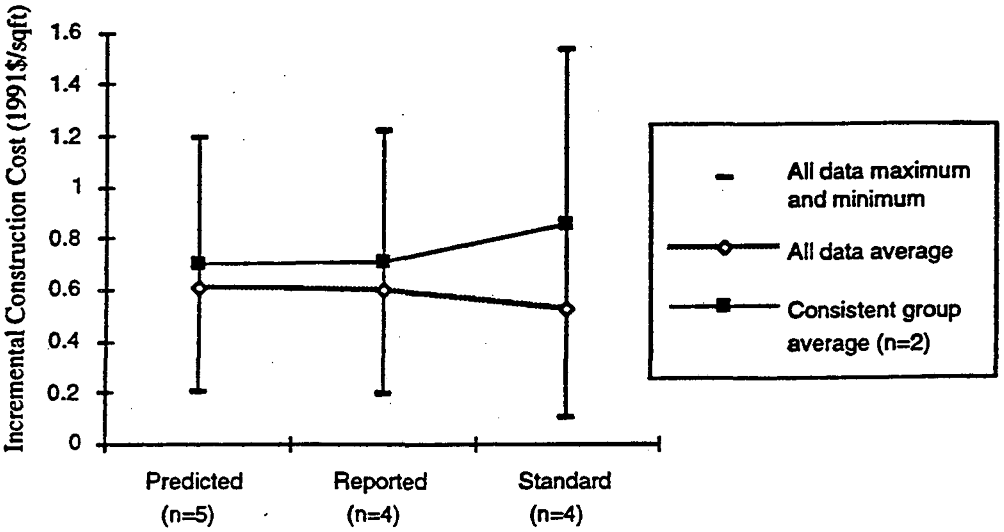


Figure 3.6. Average Predicted, Reported, and Standard costs for Economizers.

3.2 Energy Savings and Cost Effectiveness of Individual Measures

Overview of Energy Savings and Cost Effectiveness

The target levelized cost of 45 mills/kWh in $1986 is equivalent to 56 mills/kWh in 1991 based on the U.S. consumer price index. Measure cost-effectiveness from the Tuned models are primarily based on standard costs for 13 of the 18 Tuned models, and reported, or a combination of both reported and standard costs for five Tuned models. Tuned model results based on reported costs were adjusted to 1991 dollars. The cost-effectiveness of each measure is calculated according to BPA guidelines, which are equivalent to a cost-of-conserved energy based on a 3% discount rate as described in Chapter 1[3].

In this discussion we have selected the subset of 103 measures from the 18 Tuned models with Tuned energy-savings estimates, of which 81 are BPA-funded measures and 22 are owner-funded. CCEs are not available for 25 measures for several reasons, but primarily because the cost data was not sufficiently disaggregated. Table 3.2 contains a summary of the energy savings and cost-effectiveness for all 103 measures and five categories of measures: HVAC, Lighting, Other, Refrigeration, and Shell. There are two summaries for each category of measures: *all* measures for which there are Tuned energy savings, and the measures for which we have *both* Design-phase predicted and Tuned energy savings estimates (about half of the measures). The measure energy savings and cost-effectiveness tables also show the predicted costs and the costs used in the Tuned models, most of which were standard costs, although several used reported costs (Table 1.5). The cost data are *annualized incremental costs,* which is derived from the capital cost, lifetime, and discount rate (and in our case with the 6-month offset)[4]. The CCE is simply the annual cost divided by annual energy savings.

Average estimated energy savings from the Tuned model for all 103 measures is 1.04 kWh/ft^2/year, median savings is lower at 0.44 kWh/ft^{2}year. The range is from -1.68 kWh/ft^{2}year (Low-temperature air at Bellevue) to 11.4 kWh/ft^{2}year (heat-pump water-heater at McDonald's).

The distribution of savings by measure are highly skewed as shown in Figure 3.7. Among all 78 Tuned measures with cost data, 32, or 41% of the measures met the target CCE (equivalent to or below 5.6 ¢/kWh). This is slightly lower than the Design-phase predicted CCEs; predicted CCEs are available for 39 of the 78 measures. Only 18, or 46% of these measures met the CCE target. One reason many of the Design predictions did not meet the CCE target is that the cost-effectiveness screening was only to the package of measures, not to individual measures.

We can compare the Design-phase predictions of energy savings with results from the Tuned models for 46 measures to see how close the predictions were. Tuned savings are an average of 56% of the predicted savings (listed as a ratio, T/P, in the tables). This ratio is the average Tuned savings (1.33 kWh/ft^{2}year) to average Predicted savings 2.39 kWh/ft^{2}year.

Incremental measure costs used in the Tuned models are not significantly different from the costs assumed in the Design-phase predictions. Table 3.2 shows that for some subsets of measures (HVAC and Other) the costs in the Tuned models were higher than predicted. This increase partly explains the high CCEs of the HVAC equipment. Costs for the shell measures in the Tuned models were lower than predicted.

---

[3] BPA levelized cost guidelines track a stream of costs, such as O&M costs, and a stream of savings, discounted and financed at different rates. The guidelines assume a 5% inflation rate, a 3% discount rate, and financing at 8.35%. Capital costs are not financed so the 8.35% factor does not enter into the cost analysis. Combining the inflation and discount rates leads to a "nominal discount factor" of 8.15% (1.05 x 1.03 = 1.0815). The Tuned model cost analysis assumed all costs occur at the beginning of the first year, energy savings occur mid-year. The calculation is equivalent to a standard CCE based on a 3% discount rate with the savings offset by 6-months (CCE calculations generally assume costs and benefits occur simultaneously). This is equivalent to inflating the costs by half of 3% before the CCE is calculated.

[4] Annualized costs allow measures with different lifetimes to be aggregated with benefits similar to those of the *average measure life* commonly used by BPA. Recurring costs (such as O&M) can be discounted to the initial expenditure to be comparable to capital costs.

Table 3.2 Summary of Measure Energy Savings and Cost-Effectiveness.

Measure Table	**ΔEUI:** *(kWh/ft^{2}year)*		**(T/P)**	**CCE:** *(¢/kWh)*		**Cost** *($91/ft^2)*	
	Predicted	**Tuned**	**Ratio**	**Predicted**	**Tuned**	**Predicted**	**Tuned**
All Measures Average		1.04			29.06		0.81
Median		0.44			7.20		0.48
Count		103			78		84
All Measures Average	2.39	1.33	0.56	11.32	17.06	0.87	0.84
Median	1.04	0.62	0.60	5.80	6.90	0.54	0.46
Count	46	46	46	39	41	39	44
HVAC Average		0.92			40.44		1.35
Median		0.44			12.70		
Count		26			18		23
HVAC Average	2.54	1.08	0.43	14.27	28.56	1.13	1.33
Median	0.93	0.44	0.47	8.00	14.30	0.70	0.83
Count	15	15	15	13	13	13	15
Lighting Average		1.51			20.87		0.65
Median		0.70			7.50		
Count		16			15		15
Lighting Average	3.79	1.23	0.32	3.10	7.12	0.43	0.46
Median	1.42	0.84	0.59	2.40	2.70	0.43	0.26
Count	10	10	10	7	10	7	10
Other Average		3.25			2.13		0.33
Median		0.74			1.60		0.39
Count		4			3		3
Other Average	3.31	6.22	1.88	3.45	2.40	0.41	0.49
Median	3.31	6.22	1.88	3.45	2.40	0.41	0.49
Count	2	2	2	2	2	2	2
Refrigeration Average		3.56			4.47		0.95
Median		3.52			5.40		0.77
Count		7			3		3
Refrigeration Average	7.12	5.36	0.75	0.50	1.30	0.56	0.47
Median	7.12	5.36	0.75	0.50	1.30	0.56	0.47
Count	2	2	2	1	1	1	1
Shell Average		0.42			30.92		0.57
Median		0.30			7.80		0.41
Count		50			39		40
Shell Average	0.77	0.56	0.73	14.18	16.73	0.93	0.68
Median	0.60	0.48	0.80	7.15	12.00	0.85	0.58
Count	17	17	17	16	15	16	16

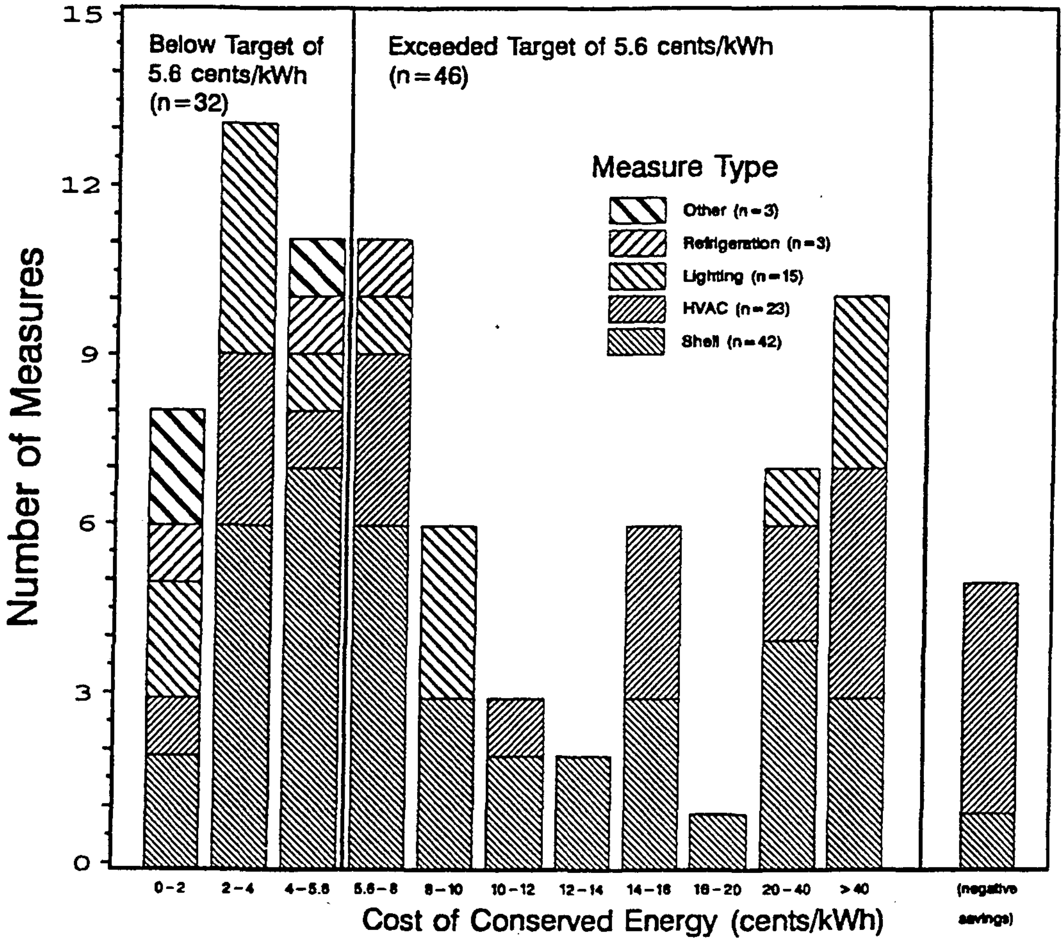


Figure 3.7. Distribution of CCEs for 78 measures with cost and Tuned energy savings from 18 buildings. Forty-one percent of the measures met the CCE target.

Failed Measures

Eight measures had negative energy savings. The reasons for the increase in energy use as a result of the efficiency measures are generally clear[5]. Five of the failed measures were HVAC measures. The ground-source heat pump at Hollywood probably did save energy because the reduction in electric-resistance heat was not captured in the Tuned model evaluation (as described in Chapter 2 and Chapter 5, see Figure 2.8). The negative savings of the HVAC system at Edgerton are further discussed below. The low-temperature air system and thermal storage at Bellevue did not save energy because nearly all similar systems are designed primarily to reduce peak demand, not energy. The cost-effectiveness analysis did not account for savings in peak demand. The increase in fan energy use outweighed savings from the night-flushing at EPUD because the massive building had very low cooling loads. Two of the eight failed measures were increases in reflectivities to reduce cooling, which failed because the buildings needed the extra heat in the winter more than they benefited from reduced cooling. The other failed measure is not really a measure, but rather the adjustment to account for the Thriftway building shell not meeting the building code.

Among the general classes of measures, the refrigeration and miscellaneous measures were the most cost-effective with median CCEs of 5.4 and 1.6 ¢/kWh, respectively (as shown in Figure 3.7). Lighting measures were the next most cost-effective at 7.5 ¢/kWh (median), followed by shell measures at 7.8

---

[5] We do not report negative CCEs for the failed measures. Negative CCE's are appropriate for those measures with a net negative cost, but not for those with negative energy savings.

¢/kWh. The HVAC measures were the least cost-effective, with median savings of 12.7 ¢/kWh. They were also the most expensive measure type, costing more than predicted. Tables 3.4 through 3.8 show the performance data for individual measures, with the building indicated by the codes shown in Table 3.3.

Table 3.3. Two-Character Building Codes.

Code	Building	Code	Building	Code	Building	Code	Building
BE	Bellevue	BK	Burger King	DI	Director	DU	Dubal
EA	Eastgate	EP	EPUD	EV	Evergreen	HO	Hollywood
EI	East Idaho	LA	Landmark	MA	Marsing	MC	McDonald's
NE	Edgerton	SI	Siskiyou	ST	STS	TH	Thriftway
TI	Tieton	WY	West Yakima				

HVAC Measures

Average energy savings among the 26 HVAC measures was 0.92 kWh/ft²year. The average CCE for the 18 measures with cost data was 40.4 ¢/kWh; but the median was far lower (yet still more than twice the target CCE at 12.7 ¢/kWh). The most cost-effective HVAC measures were the CO exhaust fan control for the parking garage at Bellevue (1.9 ¢/kWh), the air-to-water heat pump at Director (2.1 ¢/kWh), and the fan-powered terminal boxes at Eastgate (3.1 ¢/kWh). There are many difficulties in evaluating HVAC measures, as discussed in Chapter 5. Modeling and commissioning problems with the economizers and heat pumps are described further below. Results from analysis of the HVAC measures demonstrate the need for commissioning and improved O&M. The negative savings of the variable-air-volume (VAV) system at Edgerton is similar to the variable-volume variable temperature (VVT) system at Landmark (described in Section 5.2) because it is not a good example of an efficient VAV system. The Base 2-pipe fan-coil system at Edgerton was found to use less energy than the VAV system. VAV systems tend to save energy when used with central cooling and economizers, but the school has no cooling, and the HVAC comparison is based on heating only.

Table 3.4. HVAC Measure Energy Savings and Cost-Effectiveness.

	Measure	ΔEUI: *(kWh/ft²year)*			CCE: *(¢/kWh)*		Cost *($91/ft²)*	
Bldg.		**Predicted**	**Tuned**	**Ratio**	**Predicted**	**Tuned**	**Predicted**	**Tuned**
DI	Energy Management System	0.07	0.43	6.64	47.6	22.0	0.37	1.12
NE	Optimal start/stop clock		0.03			11.1	0.05	0.04
BK*	Programmable thermostat		5.77					
EA*	Variable-speed-drive controls (pump or fan)		0.88			5.9		0.61
BE	CO sensor for exhaust fans	0.28	0.45	1.59	4.2	1.9	0.11	0.08
EI	Economizer	0.93	0.14	0.16	14.0	116.1	1.19	1.53
EV	Economizer	0.43	0.08	0.18	7.3	14.3	0.29	0.1
HO	Economizer	0.77	0.05	0.06	2.8	39.7	0.20	0.16
MC*	Economizer		1.31					
SI	Economizer		0.02			316.0		0.48
BE	Low-temperature air-supply		-1.68				0.09	0
BK*	Energy-saving kitchen hood	14.03	1.37	0.10				-0.27
MC*	Exhaust fan (Supervent)	1.24	0.16	0.13		44.7		0.83
DI	Air-to-water heat pump	1.45	1.45	1.00	2.1	2.1	0.44	0.42
EI*	High-COP air-air heat pump	0.19	0.44	2.26	43.0	14.9	0.70	0.55
SI	High-COP air-air heat pump		0.91			15.9		1.21
WY	High-COP air-air heat pump	0.13	0.22	1.65	8.0	3.5	0.12	0.09
MC	Exhaust heat recovery	12.73	7.04	0.54	3.8	6.9	4.09	4.1
MA	Water-source heat pump	1.31	1.99	1.52	12.5	4.6	1.92	1.06

Table 3.4. HVAC Measure Energy Savings and Cost-Effectiveness. (cont.)

Bldg.	Measure	ΔEUI: *(kWh/ft²year)* Predicted	Tuned	Ratio	CCE: *(¢/kWh)* Predicted	Tuned	Cost *($91/ft²)* Predicted	Tuned
ST	Water-source heat pump	2.23	0.57	0.26	8.1	97.5	2.65	8.08
BE	Ice-plant thermal storage		-0.30				0.93	0.93
EP	Night flushing (HVAC)		-0.29				1.40	1.96
HO	Ground-source heat pump	0.47	-0.22	-0.49	26.3		1.03	1.17
EP	Concrete mass storage		2.20			7.8		2.92
EA	Fan-powered terminal boxes	1.80	2.03	1.13	5.8	3.1	1.53	0.93
NE	VAV reheat boxes		-1.11				0.29	2.94
	Economizers Average		0.32			121.53		0.57
	Median		0.08			77.90		0.32
	Count		5			4		4
	Economizers Average	0.71	0.09	0.13	8.03	56.70	0.56	0.60
	Median	0.77	0.08	0.16	7.30	39.70	0.29	0.16
	Count	3	3	3	3	3	3	3
	Heat Pumps Average		0.83			27.28		2.20
	Median		0.57			14.90		1.06
	Count		5			5		5
	Heat Pumps Average	0.97	0.80	1.42	17.90	30.13	1.35	2.45
	Median	0.75	0.51	1.58	10.30	9.75	1.31	0.81
	Count	4	4	4	4	4	4	4

(* on building code indicates an owner-funded measure)

Lighting Measures

Average Tuned model energy savings among the 16 lighting measures were 1.51 kWh/ft²year; median savings were 0.70 kWh/ft²year. The average CCE is high (20.9 ¢/kWh) because of three measures with CCEs greater than 60 ¢/kWh, while the median (7.5 ¢/kWh) is still above the target CCE. The most cost-effective measures were the daylighting and occupancy sensors at EPUD (1.0 ¢/kWh), and the efficient lamps, ballasts, and fixtures at Evergreen and Burger King (2.0 ¢/kWh) (Table 3.5).

Many of these same measures performed poorly in other buildings. The measure "efficient lamps, ballasts, and fixtures" reduces lighting power densities (LPDs) below the MCS code values. One reason energy savings from lowering LPDs were not as great as predicted is that in five of the buildings the installed LPD exceeded the prediction. (Section 3.3 below discusses the occupancy sensors.) The energy savings (9.6 kWh/ft²i-year) for efficient lighting at McDonald's may be overestimated because the Base LPD for the kitchen lighting at 5.4 W/ft² is probably higher than most fast-food kitchens. The Burger King Base, by contrast, was 2.2 W/ft². Kitchen lighting is exempt from code, so an assumption must be made about common practice, a decision which greatly influences the estimated measure performance. Future evaluation efforts should carefully evaluate baseline assumptions, using regional building characteristics and energy use whenever possible.

There have been problems with the daylighting systems at six of the seven Energy Edge buildings (only three were Tuned, as listed in Table 3.6). Most complaints are from dissatisfaction with stepped controls; continuous dimming designs (now more available) are less noticeable. Daylighting savings at Tieton (Table 3.5) are unique because the designers justified lower lighting levels because of the availability of daylight from the skylights. Plus, they argue that low nighttime light levels are appropriate for customers who have come in from the dark. The dimming controls at Tieton are inoperable, but the LPD is below the MCS code value, from which the savings were derived. The energy savings, therefore, cannot be directly attributed to the use of daylight to replace electric light.

Table 3.5. Lighting Measure Energy Savings and Cost-Effectiveness.

Bldg.	Measure	ΔEUI: *(kWh/ft^{2}year)* Predicted	Tuned	Ratio	CCE: *(¢/kWh)* Predicted	Tuned	Cost *($91/ft^2)* Predicted	Tuned
DU	Occupancy sensors		0.04			95.0	0.32	0.33
HO	Occupancy sensors	1.05	0.63	0.60	5.3	4.9	0.47	0.26
EA	Daylighting controls		0.08			61.4		0.6
DI	Daylighting controls & occupancy sensors	0.72	0.21	0.29	7.1	7.5	0.43	0.13
EP	Daylighting controls & occupancy sensors	2.24	1.54	0.69		1.0		0.19
BK	Efficient lamps, ballasts & fixtures	4.84	5.27	1.09	2.1	2.1	0.79	0.85
DI	Efficient lamps, ballasts & fixtures	1.40	0.60	0.43	1.8	37.2	0.19	1.71
DU	Efficient lamps, ballasts & fixtures		0.67			9.1	0.85	0.89
EA	Efficient lamps, ballasts & fixtures		1.33			9.5		0.92
EV	Efficient lamps, ballasts & fixtures	1.44	1.12	0.77		2.0		0.22
MA	Efficient lamps, ballasts & fixtures	1.13	0.94	0.83	0.4	2.8	0.07	0.39
MC	Efficient lamps, ballasts & fixtures		9.55					
NE	Efficient lamps, ballasts & fixtures	1.02	0.21	0.20	2.6	8.6	0.38	0.26
SI	Efficient lamps, ballasts & fixtures	-	0.25			66.8		2.46
TH	Efficient lamps, ballasts & fixtures	3.45	0.73	0.21	2.4	2.5	0.69	0.16
TI*	Clerestory/light shelves/skylight	20.60	1.04	0.05		2.6		0.39
	Lamps, Ballasts, Fixtures Average		2.07			15.62		0.87
	Median		0.84			8.60		0.85
	Count		10			9		9
	Lamps, Ballasts, Fixtures Average	2.21	1.48	0.59	1.86	9.20	0.42	0.60
	Median	1.42	0.84	0.60	2.10	2.65	0.38	0.33
	Count	6	6	6	5	6	5	6

(* on building code indicates a owner-funded measure)

Table 3.6. Other Measure Energy Savings and Cost-Effectiveness.

Bldg.	Measure	ΔEUI: *(kWh/ft^{2}year)* Predicted	Tuned	Ratio	CCE: *(¢/kWh)* Predicted	Tuned	Cost ($91/ft^2) Predicted	Tuned
MC	Outdoor lighting time clock & photocell	0.53	1.03	1.89	5.8	4.2	0.28	0.39
EA	Outdoor lighting timeclock		0.11			1.6		0.01
DU*	Efficient exterior lights		0.45				3.71	
MC	Heat pump water heater	6.09	11.40	1.84	1.1	0.6	0.54	0.59

(* on building code indicates a owner-funded measure)

Refrigeration and Other Miscellaneous Measures

Four measures are classified as "Other" measures, three of which are for outside lighting. The fourth is the highest energy saver, the heat pump water heater at McDonald's, with Tuned savings of 11.4 kWh/ft^{2}year[6]. The two outside lighting measures with cost data also met the cost-effectiveness criterion, with Tuned CCEs of 4.2 and 1.6 ¢/kWh.

Average and median energy savings among the seven refrigeration measures were high, at 3.6 and 3.5 kWh/ft^{2}year, respectively. As a class, the refrigeration measures were the most cost-effective all meeting the CCE target (Figure 3.7), but the sample is small. One irony is that refrigeration is not covered in the MCS code, and is somewhat outside the primary objectives of Energy Edge. More than most commercial building end uses, Refrigeration resembles an industrial process load.

---

[6] The amount of water heated was backed-out from the energy used at an assumed COP. The estimated actual water use was much higher than the projected water use so the measure saved 84% more energy than predicted.

Table 3.7. Refrigeration Measure Energy Savings and Cost-Effectiveness.

Bldg.	Measure	ΔEUI: *(kWh/ft²year)* Predicted	Tuned	Ratio	CCE: *(¢/kWh)* Predicted	Tuned	Cost ($91/ft²) Predicted	Tuned
TI	Anti-condensate heaters	10.60	3.55	0.33	0.5	1.3	0.56	0.47
TH	Uneven parallel efficient compressors	2.61						
TH	Floating-head pressure-controls	6.75						
TH*	Hot gas defrost		0.52					
TI	Refrigeration heat recovery & pressure controls		3.52			5.4		1.61
TH	Refrigeration heat recovery system	3.63	7.16	1.98				
TI	Cooler & freezer insulation		0.79			6.7		0.77

(* on building code indicates a owner-funded measure)

Table 3.8. Shell Measure Energy Savings and Cost-Effectiveness. (cont.)

Bldg.	Measure	ΔEUI: *(kWh/ft²year)* Predicted	Tuned	Ratio	CCE: *(¢/kWh)* Predicted	Tuned	Cost ($91/ft²) Predicted	Tuned
TH*	Actual building envelope	-0.30	-0.59	1.95				
DI*	Reflective interior blinds	0.22	0.02	0.10	8.0	27.9	0.19	0.07
LA*	Reflective interior blinds	0.19	-0.02	-0.15	34.1		0.73	0.22
NE	Earth berming		0.01			739.3	0.07	1.12
MC*	Perimeter insulation		0.06					
BK	Roof insulation		0.44			4.1	0.16	0.3
DI	Roof insulation		0.05			5.0		0.05
DU	Roof insulation	0.37	0.15	0.39	5.1	15.9	0.31	0.39
EI	Roof insulation		0.57			5.9	0.60	0.56
EP	Roof insulation		0.84			9.2		1.14
HO	Roof insulation		0.31			17.5		0.85
LA*	Roof insulation		0.74			1.4		0.15
MA	Roof insulation		1.03			5.2		0.78
NE	Roof insulation	1.28	0.92	0.72	6.8	12.0	1.29	1.63
SI*	Roof insulation		0.24			6.3		0.25
ST	Roof insulation		0.15					
TI*	Roof insulation		0.90			3.1		0.46
WY	Roof insulation		0.52					
NE	Thermal-break wall		0.16			41.8	0.42	0.96
EI	Wall insulation (first floor)		0.21			8.2	0.20	0.25
EI	Wall insulation (other than first floor)	0.02			34.1	0.13	0.14	
DI	Wall insulation		0.42			2.6		0.18
DU	Wall insulation	0.90	0.54	0.60	2.0	5.0	0.30	0.45
EP	Wall insulation		0.31			3.6		0.16
EV	Wall insulation		0.09			3.7		0.05
HO	Wall insulation		0.05			5.0		0.04
MA	Wall insulation		1.12			11.1		1.82
MC*	Wall insulation		0.15					
NE	Wall insulation		0.08			13.0	0.16	0.16
SI*	Wall insulation		0.41			2.8		0.19
TI*	Wall insulation		0.29			4.3		0.2
WY	Wall insulation		0.12			5.1		0.12
LA	Wall insulation w/finish		0.97			13.3	2.17	1.89
ST	Wall insulation w/finish		0.60					

Table 3.8. Shell Measure Energy Savings and Cost-Effectiveness. (cont.)

	Measure	**ΔEUI:** *(kWh/ft²year)*			**CCE:** *(¢/kWh)*		**Cost ($91/ft²)**	
Bldg.		**Predicted**	**Tuned**	**Ratio**	**Predicted**	**Tuned**	**Predicted**	**Tuned**
EP	Trellis shading	0.20	0.06	0.31	86.3	83.6	2.05	0.61
MA	Reflective roofing		-0.02					
WY*	Reflective roofing		0.22					
DU	Vestibule	0.43	1.36	3.16	3.7	1.1	0.30	0.3
LA	Low-E, tinted windows w/thermal break frames	1.66	1.20	0.71	5.3	8.0	0.99	1.07
NE	Double-glazed, low-E windows w/thermal break frames	1.54	0.80	0.52	6.8	6.1	1.17	0.55
MA	Double-glazed, tinted, low-E windows w/thermal break frames	0.51	0.65	1.26	4.3	5.9	0.25	0.43
SI*	Double-glazed windows w/thermal break frames	0.60	0.48	0.79	22.2	22.4	1.95	1.56
DU	Low-E windows	0.24	0.14	0.60	9.4	15.7	0.25	0.25
EA	Low-E windows	1.90	2.14	1.13	7.5	2.7	1.58	0.63
EI	Low-E windows	0.63	0.40	0.64	13.8	22.6	0.96	1.01
WY	Low-E windows		0.05					
BE	Low-E, tinted windows	0.68	0.90	1.32	3.4	7.8	0.26	0.78
ST	Low-E, tinted windows	1.97	0.44	0.23	8.1	14.2	2.35	0.92
TI*	Thermal-break window frames		0.22			9.4		0.31
WY	Thermal-break window frames		0.09					
Wall Instulation Average			0.33			5.62		0.34
Median			0.29			4.65		0.17
Count			11			10		10
Wall Instulation Average		0.90	0.54	0.60	2.00	5.00	0.30	0.45
Median		0.90	0.54	0.60	2.00	5.00	0.30	0.45
Count		1	1	1	1	1	1	1
Roof Insulation Average			0.53			7.78		0.60
Median			0.52			5.90		0.46
Count			13			11		11
Roof Insulation Average		0.83	0.54	0.55	5.95	13.95	0.80	1.01
Median		0.83	0.54	0.55	5.95	13.95	0.80	1.01
Count		2	2	2	2	2	2	2
Windows Average			0.63			11.48		0.75
Median			0.46			8.70		0.71
Count			12			10		10
Windows Average		1.08	0.79	0.80	8.98	11.71	1.08	0.80
Median		0.68	0.65	0.71	7.50	8.00	0.99	0.78
Count		9	9	9	9	9	9	9

(*on building code indicates a owner-funded measure)

Shell Measures

Average and median energy savings of the 50 shell measures (windows, wall, and roof insulation) were 0.42 and 0.30 kWh/ft²year, respectively. For the 17 measures with both Design-phase predicted and Tuned savings estimates, Tuned savings averaged 84% of predicted (high for Energy Edge). For the 16 measures with cost data, the average predicted CCE was 14.2 ¢/kWh, well above the target, with Tuned CCEs slightly higher at 16.7 ¢/kWh.

The window measures consist of low-emissivity glazing replacing double-paned (or single-paned at the two schools) and double-paned with thermal-break frames in place of double-paned without thermal breaks. The most common wall insulation measure was to improve a baseline R-11 wall to R-19, and the most common roof insulation measure was the use of R-30 instead of R-11 or R-19. The window and roof measures generally saved more energy than the wall insulation, but the wall measures were the most cost-effective, and on average, met the cost-effectiveness criterion. The three measures to reduce solar gains did not perform well, probably because of higher than predicted heating loads.

One reason the measures saved less than predicted is there were many changes in both the measure and the baseline shell characteristics. At East Idaho, for example, the Base glazing in the prediction was single-paned, but double-paned was used in the Tuned Base. At Dubal, the predicted Base wall insulation was R-7 and the Tuned Base was R-11. Similar changes occurred at Hollywood and Landmark. The effective insulation values installed at STS and Evergreen were much less than that in the predictions.

At Evergreen, the effective roof insulation was reduced because a roof leak caused water damage to the insulation, which was never repaired. The status of failed or partially-failed measures has been difficult to track and model. There was no Tuned energy savings estimate for the partially failed roof measure at Evergreen.

Measures Dropped from Tuned Models

In Chapter 1 we reviewed the CCEs for each building's complete package of measures from the Design-phase predicted and Tuned models. Section 1.3 discussed reasons for differences between predicted and Tuned energy savings, further discussed in Chapter 5. Each measure was assigned a status code to track what happened from the Design-phase predicted to its Tuned models. Among the Tuned models, four measures were not installed; three of these four were improvements to lighting systems. Seven measures were added to the buildings that were not in the predictions—HVAC controls, exterior lighting, and shell measures. Many measures included in the actual buildings were not included in the Tuned models because of measure failure, partial measure failure, or ambiguity regarding modeling methods. Failed measures included daylighting controls, VAV reheat boxes (negative energy savings), and anti-condensate heaters. Partially-failed measures that were only sometimes modeled included economizers, occupancy sensors, roof insulation, and daylighting systems. Measures that were dropped because of the ambiguities of the baseline systems or partial failure of the efficient system include HVAC systems (VVT), infiltration measures (vestibules and vapor barriers), and refrigeration evaporator motors.

3.3 Performance of Individual Measures

Earlier Energy Edge reports have discussed three groups of measures to further understand their performance (Diamond et al., 1992). The three groups of measures were: occupancy sensors; high-efficiency heat pumps; and economizers. These measures were selected because of their relative importance to the project and to explore analysis issues beyond the Tuned models. We briefly review key findings from the earlier discussion (Diamond et al., 1992).

Occupancy Sensors

Energy savings from occupancy sensors were lower than predicted and difficult to model because of the subjectivity of defining the baseline control strategy. The Design-phase predictions contain minimal information about how the early energy savings estimates were derived. Analysis of end-use metered lighting data did not provide information on the occupancy sensors because only a small fraction of the lights on each circuit were controlled by the sensors. So, anecdotal information and engineering estimates were used to model the sensors by adjusting the LPDs to account for an average reduction in power. In the Dubal pilot study the modeled reduction in the LPD during daytime hours ranged from 10 to 50%.

Many of the sensors were poorly calibrated and dropped from the Tuned models. Anecdotes about occupancy sensors are amusing and plentiful. One favorite (at Montgomery) is the case of salesmen required to be in their sales area for a fixed work schedule. They rigged fans with paper streamers near the motion sensors to keep the lights on; the fans were controlled with a timeclock set to their work schedules.

High Efficiency Heat Pumps

High efficiency (or high COP) air-to-air heat pumps were installed in six Energy Edge buildings. We found operational problems in each case. We selected Siskiyou to analyze because of the early availability of a completed Tuned model and multi-year hourly end-use data. Our evaluation focused on the energy performance and heating characteristics of the heat pumps, based on annual compressor energy use and average COP values, as described in Piette et al., (1992). To review the performance of the HVAC systems at Siskiyou we compared the calibrated DOE-2 simulation results with the monitored data. We compared the manufacturer's rated COP with the hourly average COP with and without fan energy use. The average measured COP for the largest heat pump was 83% of the rated COP (without fan energy).

The analysis turned up several useful results regarding the performance of the heat pumps. The COP measurements in Siskiyou's largest heat pump showed that it had been operating well, and slightly better than the simulation model results. While the heat pump was performing well, the use of electric resistance heat could be further reduced with a ramp-up thermostat. We base this conclusion on analysis of the hourly HVAC load shapes that showed most of the resistance heat occurred during the morning warm-up hours. The HVAC electric load profile had a significant morning peak at 7 a.m., ten times greater than the average winter hourly load at 6 a.m. We found that the DOE-2 model of HVAC energy use differed significantly in fan, compressor heating, resistance heating, and cooling energy use. The simulation overestimated fan energy use since it is modeled as "always-on" during every hour with any heat pump operation (even just a few minutes), which is not the case in the actual building.

Air Economizers

Air economizers are present as efficiency measures in six buildings. Economizers allow increased quantities of outside air into the HVAC ducts when the thermostat calls for cooling and the outside air has acceptable conditions of temperature and humidity. Since MCS requires economizers for fan systems with an air flow greater than 3500 cfm, we only analyzed them in the smaller buildings where they were measures. The field audits reported numerous problems with their operation, including frozen dampers (East Idaho), improperly set wiring (O'Ryan), and incorrect settings (Evergreen, Siskiyou).

The parameters to calculate the outside air fraction in the HVAC supply air are return, mixed, and outside dry-bulb temperatures. We also examined HVAC energy use, which consists of fan energy during a full hour of economizer operation. Large buildings tend to have integrated economizers that allow the compressor to operate while the dampers increase quantities of outside air, but most smaller systems are not integrated. With a non-integrated economizers the compressor is always off when the outside air quantities are increased, so the supply air temperature equals the mixed temperature. We verified that the economizer is operating when the supply air temperature equals the mixed air temperature.

The outside air fraction for Siskiyou's largest heat pump was relatively constant at about 35 to 39%, suggesting little operation of the economizer. At East Idaho, the heat pump showed two modes of operation, with a minimum outside air fraction of about 10% and a maximum of about 50%, much less than the 100% fraction we expect. Unfortunately, the uncertainty in the temperature measurements has a greater effect on outside air fraction estimates at smaller temperature differentials, such as during hours of economizer operation.

The economizers we studied were all small units which may be inherently less reliable than larger systems. The failure of the *small* economizers illustrates the need for diagnostic testing. Another possibility is to build a self-diagnostic indicator into the system to alert operators to malfunctions.

Damper Position and HVAC Energy

To explore the impacts of the fixed outside-air fractions at Siskiyou we ran three additional simulations with the Tuned model. Ideally, the dampers should close in cold periods to reduce the volume of cold outside air in the mixing box. To evaluate how much the fixed dampers increased the heating energy use we examined four scenarios:

- Fan always-on, 10% outside air
- Fan always-on, 35% outside air
- Fan on-demand, 10% outside air
- Fan on-demand, 35% outside air

The last mode represents the conditions in the Tuned model. Changing the damper position from 35% to 10% outside air reduces heating energy use by more than a factor of two for both the fan on-demand and always-on modes. The change in cooling energy was relatively minor. Based on the reported maximum occupancy of 13 people, the ventilation requirements by the MCS of 5 ft^3 per person of fresh air, and the heat pump capacity of 2000 ft^3, the minimum acceptable outside air fraction is 3%.

An important lesson was that the energy savings from better control and operation are likely to be as large, if not larger, than the energy savings from the ECMs. The Tuned model savings for the improved heat pump COP was 2740 kWh. The heating energy savings that may have been achieved if the dampers closed more tightly to allow less outside air may have been even greater than the savings from the improved heat pump COP. These analysis highlight the need for better commissioning and O&M.

Chapter 4. Ensuing Optimal Performance of Measures

Key Findings in this Chapter

- Commissioning of energy-efficiency measures during building start-up is crucial to ensure that energy savings are achieved. Over two-thirds of the problems with measures in the Energy Edge buildings would likely have been caught and corrected with proper commissioning.
- Energy savings from the pilot commissioning study at the Director building resulted in reducing energy use by 8%. Further opportunities for another 4% in energy savings were identified.

4.0 Introduction

Buildings and energy-efficiency measures often do not perform as well in practice as expected at the design stage. Energy Edge has confirmed this fact. Early in the project, participants recognized that quality control during construction and post-construction commissioning were essential steps to ensure effective, sustained performance of energy-efficiency measures. We use the term "commissioning" as defined by Yoder and Kaplan (1992) as,

> "...a set of procedures, responsibilities, and methods involved in advancing a total system from a state of static physical installation to a state of full working order in accordance with design intent. At the same time, the operating staff are instructed in system operations and maintenance."

The energy-efficiency measures in Energy Edge were not commissioned in the formal sense of the word. However, in recognition of the need for commissioning, Commissioning guidelines was developed (late in the project history) and a pilot commissioning study was conducted to test the guidelines (PECI, 1992). The guidelines describe how to develop commissioning specifications, document design intent, test start-up procedures, perform functional tests, and design operations and maintenance manuals. Several electric utilities currently include commissioning as part of their commercial Demand-side Management programs, many of which were motivated by experience from Energy Edge (Benner and Bjornskov, 1993).

This chapter provides an overview of the type of problems found in the Energy Edge buildings. We describe design, installation, product performance, and operations and maintenance problems with 42 of the nearly 200 measures evaluated among the 28 Energy Edge buildings. The information from this analysis came from anecdotal comments in the operations and maintenance audits. The measures in greatest need of commissioning are control measures, not surprising, as their proper adjustment is required for both energy performance and occupant satisfaction. The chapter also includes a description of the results from the Director pilot commissioning study, where lighting control modifications reduced whole-building energy use by 8%. The pilot study was conducted to test the commissioning guidelines. Our analysis shows how regression analysis can be used to derive an estimate of weather-normalized energy savings from operations, control, and maintenance improvements. Further details on the methodology used to estimate the energy savings are presented in Appendix A4.

4.1 Operations and Maintenance Issues

Information on O&M problems were developed from anecdotal comments contained in the O&M audits and reports from the project sponsors on the status of various measures. The O&M audits were designed to identify if the measure deviated from the design specifications and how it was maintained. Unfortunately, there was a large range in the quality and quantity of information compiled by the auditors. We do not have a comparable set of comments for all of the measures in all 28 buildings.

Table 4.1 summarizes problems associated with 42 of the 170 measures for which we had some documentation. To evaluate trends in the data we assigned each problem to one or two of the following categories: design (D), product performance (P), installation (I) and O&M (O). Difficulties that might not have been corrected if commissioning had occurred are indicated with an asterisk (*). Most of the problems would probably have been corrected with commissioning. For example, the pump on the ground-water-source heat pump at the STS building is manually controlled and often operates continuously. Commissioning should have identified both the problem and the party in a position to modify the controls.

Table 4.1. Performance Problems with Selected Measures.

Building	Measure	Severity	Comments	Type
	HVAC Measures			
Boardwalk	Air-Air heat exchanger	H	Disabled; comfort problems	D
Siskiyou	Economizer	H	Set point limited effectiveness	OP
Hollywood	Economizer	H	Air leak; access difficult	IP
Evergreen	Economizer	H	Problems w/setting & dampers	OP
East Idaho	Economizer	H	Damper doesn't move correctly	OP
O'Ryan	Economizer	H	Wired incorrectly	I
Director	EMCS	H	Only partial operation	IO
EPUD	EMCS	H	Complex, partial operation	DOI
McDonald's	Exhaust heat recovery	L	Washing system flooded	O*
Hollywood	Ground-source heat pump	M	Control problems	D
East Idaho	Efficient air-air heat pump	?	Poor thermostat location	PI
Caddis	Efficient air-air heat pump	?	Discomfort & design problems	D
Edgerton	VAV reheat boxes	M	Air control problems	O
STS	Water-source heat pump	H	Water pump runs constantly	DI
Boardwalk	Water-source heat pump	M	Filter & pump problems	OD
Marsing	Water-source heat pump	M	Back-up boiler clogged	I
	Lighting Measures			
Dubal	Efficient lamps, bal. & fixt.	M	100 W incd. lamps added	DO
Evergreen	Efficient lamps, bal. & fixt.	M	Track lighting added	I
Tieton	Daylighting controls	H	Not properly installed	I
Siskiyou	Daylighting controls	H	Not functioning	DI
Hollywood	Daylighting controls	H	Not functioning; skylights dirty	DO
Director	Daylighting controls	H	Not functioning; overridden	DI
Eastgate	Daylighting controls	L	Partial operation	DI
EPUD	Daylighting controls	M	Limited operation	DI
Thriftway	Lighting timeclock	H	Replaced, still limited use	DO
Dubal	Occupancy sensors	M	False trips from hallways	IP
Hollywood	Occupancy sensors	M	False trips, often overridden	IP
Thriftway	Occupancy sensors	M	Some ineffective; not modeled	IP
	Other Measures			
Skippers	Exhaust kitchen hood	?	Not operated properly by staff	O
McDonald's	Exterior lighting	M	Controls not used; manual oper.	O
Director	Garage CO sensor	M	Frequent calibration needed	DOP
McDonald's	Heat pump water heater	L	Back-up ht. not installed, fixed	I
Tieton	Humidistat controls	L	Controls not installed, fixed	I
Thriftway	Humidistat controls	H	Controls not function	IO
Roger's	Insulated garage door	M	Door control problem	D
	Shell Measures			
Edgerton	Low-E windows	L	One developed moisture	P*
EWEB	Low-E windows	M	Some installed incorrectly	I
Dubal	Roof insulation	M	Some water damage	DI*
Evergreen	Roof insulation	H	Removed after leak, not fixed	O*
EPUD	Trellis shading	?	Slow vegetation growth	DI
East Idaho	Wall insulation	L	Missing some insulation	I*
Roger's	Wall insulation	M	Lower R-value than specified	I*

Severity: L-Low, M-Medium, H-High, ?-Don't Know.
Type of Problem: D-Design, P-Product, I-Installation, O-O&M
*Might not have been corrected with commissioning.

Commissioning could have caught over two-thirds of the measure performance problems. Energy-efficiency measures can be categorized as "static" and "dynamic" measures. Static measures are those that do not change their state, such as extra wall or roof insulation. Active measures are those that involve several modes of operation, such as control or HVAC measures. Comprehensive commissioning can address both static and dynamics measures, although often commissioning is restricted to dynamic measures. Therefore, commissioning may not have identified shell measures if only dynamic commissioning was conducted. Some operations and maintenance problems or one-time system malfunctions would not be identified with commissioning.

Based on the general categorization of measure problems presented in this table, the most common were installation problems, followed by O&M, design, and product performance problems. Commissioning might have caught about two-thirds of the problems, while providing feedback about the original design concepts and helping to define proper O&M. Problems that tend to occur with individual products, such as malfunctioning economizer dampers or occupancy sensors that are difficult to calibrate, should be reported to utility Demand-side Management (DSM) planners and evaluators, building designers, and to manufacturers to modify the product. A few of the problems reported in the O&M audits were repaired (e.g., the back-up heat for the water heater at McDonald's).

Most of the problems noted resulted in decreased energy savings. Problems that have the most severe impact on reducing energy savings are indicated with an H (High severity). Some efficiency measures were installed but are not operational, most often the case with control measures. Lighting control measures, including daylight dimming, occupancy sensors, and the timeclock are the most prominent "failed" measures, with zero energy savings. Many of these measures, particularly the occupancy sensors, are actually "partially-failed" measures, dropped from the tuned model because of the lack of detailed information about their performance throughout different zones in a building. These results highlight the need to commission control systems.

4.2 Pilot Commissioning Study

Director is an 80 kft^2, nine-story office building in Portland Oregon It was one of two major renovations in Energy Edge, and thus was not a completely new building. After the renovation (including efficiency measure installation), the building operated for several years before the commissioning study began, so it may be more accurately considered a "recommissioning" study (though no original commissioning was done). The energy-efficiency measures affect all of the major end-uses and building systems, and include lighting, HVAC, envelope, and control measures. Table 4.2 lists each measure with comments on its operating status before and after the commissioning. The commissioning tests revealed problems regarding lack of documentation, poor O&M practices, equipment and system performance problems, and improper installation (PECI 1992). Extensive tests were conducted to examine the operation of the water-loop heat pump, which includes 93 unitary heat pumps, a 30-ton water-to-air heat pump for loop heating (and backup cooling), and a 125-ton cooling tower. The final commissioning report includes an extensive list of recommendations for optimal whole-building performance emphasizing modifications to the heating, cooling, and ventilation systems (HVAC).

LBL analyzed hourly end-use data—monitored before, during, and after the commissioning activities—compiled for the tuned model calibration. In 1991 the building used only 12 kWh/ft^{2}year (plus a small amount of gas used during cold periods to boost the heat-pump water-loop temperature). Quantifying the total energy savings resulting from all of the modifications related to the commissioning study is complicated by variations in hours of occupancy, change in tenancy, and weather. We were able, however, to quantify energy savings from several specific actions, as described below.

Table 4.2. Findings from Pilot Commissioning Study at the Director Building.

Measure	Status Before Commissioning	Action
Lighting		
T-8 32 W lamps	Installed, 34 W lamps also used	None, audited
PL-13 CFLs	Installed, working	None, audited
Occupancy Sensors	Installed, most effective	None, audited
Stepped Daylighting	Not functioning, disabled	None, audited
Hydronic Heat Pump		
Air-to-Water Heat Pump	Won't hold charge, dirty condenser	Refrigerant charged
Heat Recovery in Elevator Shaft	Inefficient, dirty filter	Recommend modifications
2-speed Heat Pump Controls	Some missing, wiring errors	None, design reviewed
EMCS	Limited use	Control domain enhanced
Garage CO Control	Needs frequent calibration	Calibrated
Shell		
Wall & Roof Insulation	Assumed working	None, audited
Reflective Shades	Dependent on occupant use	None, audited
Window Weatherstripping	Dependent on closing windows	None, audited

Energy Savings from Lighting Controls

During 1991, prior to the modifications, many of the lighting circuits were left on all night. In early summer 1992, sweep controls were added to the EMCS to turn off the lights at 7 p.m., 10:30 p.m., and midnight. Occupants can override the controls using local switches. Figure 4.1 shows three average hourly lighting load shapes before and after the sweeps were installed. The top curve is the average weekday load for 1991 for four floors (3, 7, 8, and 9) before the sweeps were installed. The middle curve shows average weekday load for June 1992 after the sweeps were installed, showing the decrease in nighttime energy use. The lowest curve is the 4th floor load, which includes a significant amount of occupancy sensor control. Data plotted are average energy use normalized to the maximum measured peak for the circuit. Based on one month's data with the controls in place, we estimated that direct energy savings for lighting would be 8% of whole-building annual energy use (about 73 MWh, or 0.9 kWh/ft^{2}year). (We did not estimate interactive HVAC savings.)

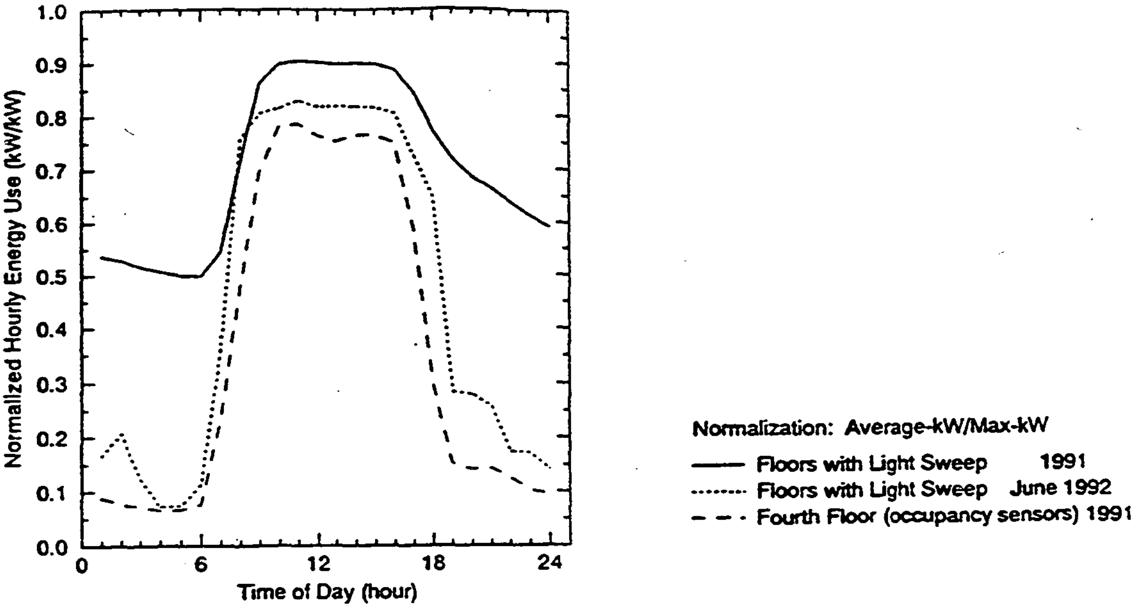


Figure 4.1. Average lighting load shapes at Director

The third, and lowest curve is the fourth floor lighting, where occupancy sensor controls are predominant. Occupancy sensors cause the average lighting load to be lower than floors with timeclock controls because lights are off when people leave individual offices. We found, as the figure illustrates, that the slope of the daily load curve during the morning and evening periods is less steep with occupancy sensor control, showing the variation in occupant arrival and departure times. The fourth and fifth floors of the building have more individual offices than the other floors (which have more open-floor plans), allowing occupancy sensors to be effective.

Energy Savings from Night Setback Control

Enhancement of the EMCS timeclock control of the unitary water-to-air heat pumps were initiated during the commissioning study. Prior to the commissioning study the unitary heat pumps and the water-loop pump operated 24-hours per day. Night set-back control was added for floors 6, 7, and 9, reducing annual energy use during the night by 22% (corrected for changes in weather). Morning energy use increased by 24%, resulting in no net energy savings. However, the commissioning study recommended that the water-loop circulation pumps should be shut off at night, which would save about 4% of annual energy use. For this control function to be operational, the unitary heat pumps must be shut off. The building management is considering whether to adopt the recommendations.

The only HVAC equipment integrated into the EMCS are 41 of the 93 unitary heat pumps; the EMCS has been used primarily for fire and security systems. The EMCS program to schedule the run times of the heat pumps was disabled after the building operator had trouble maintaining control of the building during a cold period. On August 14, 1991, EMCS control of the 41 heat pumps on floors six through nine was initiated to test the feasibility of a night setback control strategy from 10 p.m. to 5 a.m. The night setback was used from August 15, 1991 to February 13, 1992. We used January 1, 1991 through August 12, 1991 as a "baseline" period when the heat pumps were *on* 24-hours per day.

To estimate energy savings from the timeclock control we performed a series of regressions correlating hourly outside temperature and heat pump energy use. Further details on the method are presented in Appendix A-4 (and in Nordman and Meier, 1988). The technique involved deriving an annual estimate of heat pump energy use for each floor, separated by weekends and weekdays. Weekday annualized electricity use is shown in Table 4.3. The greatest change in energy use is on the 7th floor during the morning (midnight-6 a.m.) where electricity use decreased by two-thirds (from 4.5 MWh to 1.5 MWh). There was not net savings for the sum of all floors where night setback was added. Overall, for all three floors, early-morning electricity use decreased 31%, mid-morning electricity use increased 24%, afternoon energy use increased 6%, and evening energy use decreased 14%.

Table 4.3. Annualized weekday Heat Pump Electricity Use (MWh) from weather regressions.

Floor	Control Mode	Electricity Use by Time of Day *(MWh)*				
		Total	**1-6**	**7-12**	**13-18**	**19-24**
Six	**24 hour use**	28.4	5.1	7.0	10.0	6.4
	With night set back	30.5	4.2	9.1	11.1	6.2
Seven	**24 hour use**	22.3	4.5	5.3	7.0	5.6
	With night set back	23.0	1.5	8.3	8.7	4.5
Nine	**24 hour use**	20.1	2.6	5.3	7.9	4.3
	With night set back	16.9	2.7	4.4	6.6	3.2
Six to Nine	**24 hour use**	70.8	12.1	17.6	24.9	16.2
	With night set back	70.5	8.3	21.8	26.5	13.9
	Difference *(MWh)*	0.3	3.8	-4.2	1.6	2.3
	% Difference	0%	-31%	+24%	6%	-14%
All floors	**24 hour use**	185.2	34.2	45.9	63.4	41.7
	With night set back	172.5	29.6	47.7	59.3	35.9
	Difference *(MWh)*	2.7	4.6	-1.7	4.1	5.8
	% Difference	-7%	-13%	+4%	-6%	-14%

The estimate of total annual savings was based on combining the weekend and weekday regression results. For the floors 6, 7, and 9 we estimated that annual energy use for the unitary heat pumps "always on" was 87 MWh. With the night setback schedule, energy use decreased by 3% (84 MWh). Another finding in the analysis of the night setback is that the setback temperature of 55°F was never reached. The Director Building is a fairly massive, brick building, and does not cool down quickly. It does, however, heat up, as the regression results indicate.

Total Energy Savings from Commissioning

Total savings in heat pump energy use for all nine floors was 7%, probably due to differences in energy for all of the unitary heat pumps as a results of other commissioning and O&M improvements. Overall energy savings for the control enhancements attempted at Director are presented in Table 4.4.

Table 4.4. Energy Use and Savings from Commissioning at the Director Building.

1991 Annual Electricity Use	11.9	kWh/ft^{2}year
Savings from Lighting Sweeps	0.9	kWh/ft^{2}year
Direct savings from Heat Pump Night Setback		negligible
Estimated Savings from Heat Pump Commissioning	0.8	kWh/ft^{2}year
Potential Savings of Pump Control	0.5	kWh/ft^{2}year

Daily Regression Analysis of Whole-Building Energy Use

It is uncommon for building energy analysts to have hourly end-use data to aid the analysis. However, it may be possible to compile whole-building daily data from utility meters from daily meter readings. We explored the daily whole-building total energy use to see how useful these data are in evaluating the energy savings from commissioning. Similar to the hourly regressions, we regressed daily energy use with average daily temperatures. Of course, in contrast to the hourly analysis, with daily data we lose the ability to identify differences in energy use by time of day.

Figures 4.2 and 4.3 show the daily whole-building energy use vs. outside temperature for the periods with and without the night scheduling, respectively. Weekday energy use differed slightly. There is no heating slope for the period before commissioning and night-setback (Figure 4.2) showing that there was probably more simultaneous heating and cooling than in post-commissioning and night setback periods (Figure 4.3). Furthermore, after the commissioning and control changes took place, the building consumes less energy, especially when average outside temperatures range from 40-55 °F.

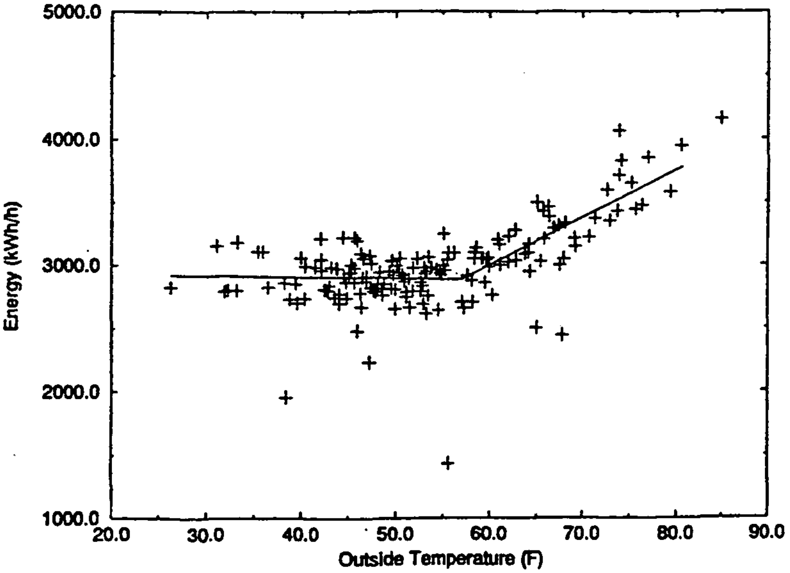


Figure 4.2. Regression of daily whole-building energy use vs. outside temperature before commissioning and control changes. The figure shows that there is no increase in heating during low average outside temperatures.

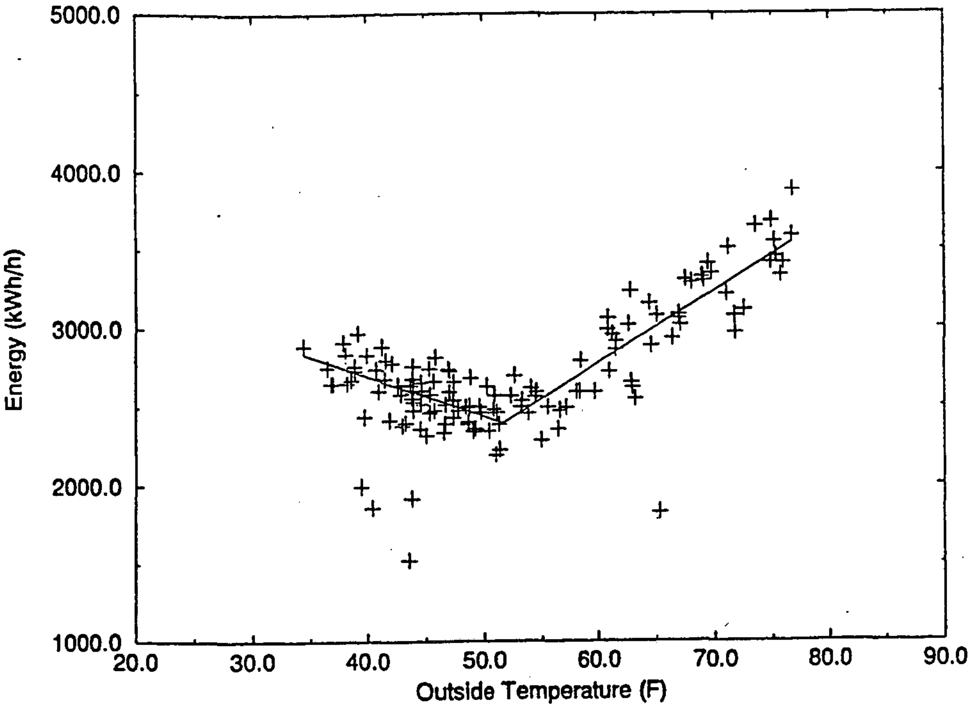


Figure 4.3. Regressions of daily whole-building energy use vs. outside temperature after commissioning and control changes. The heating and cooling curves are lowered, showing less energy use for the same outside temperature.

4.3 Recommendations for Future Programs

Several electric utilities currently include commissioning as part of their commercial DSM programs, many of which were motivated by the experience with energy-efficiency measures from Energy Edge (e.g., Yoder and Kaplan, 1992). Few results are available to demonstrate the energy savings and other benefits, such as improvements in indoor air quality, occupant satisfaction, and O&M costs, resulting from commissioning. Careful tracking of commissioning costs and benefits are needed to identify which procedures are most successful and should become elements of common practice. Research is underway to improve the use of EMCS, available in most large buildings, to assist in the evaluation of measures, commissioning, and assessment of ongoing O&M.

Chapter 5. Methodology Assessment

Key Findings in the Chapter

- Although it took about 400 hours to develop each Tuned model, the results are uncertain for some measures because of difficulties defining baseline assumptions to reflect the building code and current practice. Measures that were most difficult to model are HVAC and lighting controls, and infiltration measures.
- Shortcomings in the project documentation hampered comparisons of building characteristics, and measure definitions, costs, and O&M problems.
- Continuous end-use monitoring was expensive and often did not provide suitable information for the analysis of measure performance. Direct tests, combined with functional and diagnostic testing for commissioning, could have been useful to determine a measure's impact.

5.0 Introduction

It is nearly impossible to *measure* the energy saved from an energy-conservation strategy because we cannot know how much energy would have been consumed if another set of building systems or operating strategies were in place during a given period. We can only *estimate* savings. As discussed in Chapter 1, this problem is particularly significant with new buildings because of difficulties in defining baseline conditions. Analysis of measured data greatly increases our understanding of the performance of measures and building systems. Measured energy data help provide information on technology performance characteristics and building conditions, and help identify installation and operating problems to improve our understanding of what drives energy use.

The Energy Edge program has proved to be a fertile testing ground for evaluating methods for assessing commercial building performance. This chapter discusses the strengths and weaknesses of the evaluation methodology[1]. We begin with a review of the four Tuning methodologies used to evaluate the Energy Edge buildings. Next we discuss the results from the Tuned model for the Landmark building to illustrate the types of data available from each of the models and issues in interpreting the results. The third section discusses the strengths and weaknesses of the Tuned model evaluation approach, highlighting the difficulties in defining baseline systems and shortcomings of simulation models. Section 5.4 reviews differences between the Design-phase and Tuned models to help explain why energy savings from the Tuned models were often lower than predicted. The fifth section summarizes the evaluation activities beyond the Tuned model effort and discusses shortcomings of the analysis from a broad research perspective. The sixth section reviews suggestions for future program evaluation methodologies, including a description Energy Management and Control System (EMCS) as data loggers (with further details in Appendix 5). The final section compares the performance of the measures from the Energy Edge Tuned models with the energy savings assumed in the Energy Smart Design Prescriptive Path for small buildings (widely used throughout the Northwest).

5.1 Model Tuning Activities

"Tuning" a building simulation model is the process of adjusting a model to match measured data from an actual building, to increase the confidence in measure savings estimates. The time interval (e.g., hourly, monthly, seasonal, annual), and type of energy use (e.g., whole-building vs. end-use energy) vary for most of the methods explored, as described below, but the principle is the same. The exception being the STEM method, described below.

The development of Tuned simulation models of the Energy Edge buildings followed the development of two other sets of models: those used in making Design-phase measure savings predictions; and the "As-built" models based on the actual construction details, equipment inventories, and schedules. This information came from a a standardized building *Documentation Package* and periodic, on-site *Operations and Maintenance (O&M) Audits.* The As-built model is the starting point for

---

[1] Appendix A5 presents suggestions for future research topics identified to address outstanding issues in the evaluation.

the model tuning. Once calibrated with the end-use data it becomes the Tuned model. Simulation models can be used for a variety of purposes. In Energy Edge they are used to estimate measure energy savings.

Model Tuning Methodologies

The four modeling approaches differ in the way the As-Built model is calibrated or *Tuned* with monitored data, as described below:

- **Daily Profile Tuning (DPT)**
  The pilot study of the Dubal Beck office building explored the development of model tuning with hourly load profiles for various end-use loads and several average day-types (Kaplan Engineering, 1989). This method (initially known as the "fine-tune") was found to be burdensome because of the effort required to process and review detailed hourly data (an MCT model was subsequently developed.)
- **Monthly end-use energy Consumption Tuning (MCT)**
  The second modeling strategy used within Energy Edge, MCT, is a "quick-tune" approach. This is the standard method for the Energy Edge modeling analysis, applied to 17 of the 18 buildings (all except Burger King). Buildings were tuned until the simulated HVAC end-use matched to within 30% of the monthly monitored end-use, and within 20% of seasonal end-uses. "Tuning tolerances" varied slightly among the buildings and hourly data were used to debug the models. As the program progressed, better use was made of the monitored data within the model tuning with assistance from LBL. Examples of tuning adjustments include: using monitored lighting power to calibrate the modeled lighting power, adjusting outside-air fractions based on return air, mixed air, and outside temperatures, and modifying heating, cooling, or refrigeration system efficiencies based on measured data.
- **Short-Term Energy Measurements Tuning (STEM)**
  This methodology, based on detailed short-term measurements, was developed to incorporate results from a standard set of thermal tests that typically took place over a weekend. STEM, developed at the National Renewable Energy Laboratory (NREL), involves co-heating tests to estimate building conductance, infiltration loads, solar gains, thermal mass, plus heating, ventilation, and air-conditioning (HVAC) performance. This information is used to calibrate various simulation inputs. STEM is oriented towards evaluating HVAC and shell characteristics, providing little information on lighting and control systems. STEM model calibration was applied to East Idaho, for which an MCT model was also developed. STEM tests were also conducted at the EPUD building, but STEM model tuning was not done.
- **Whole-Building Monthly Consumption Tuning**
  Because of the lack of end-use monitored data at many buildings, whole-building tuning was applied at Burger King. The tuning consisted of matching monthly gas and electricity consumption from the model to the utility bills.

Each method uses actual weather data to tune the DOE-2 model to monitored energy use data. Long-term average weather are then used to model the energy-efficiency measures based on average conditions.

Three reports summarize experience from the modeling: Kaplan Engineering and PECI, 1992; Kaplan Engineering, 1992; and Kaplan Engineering and PECI, 1993. The last of the three references summarized key lessons from the modeling, which was far more complex than anticipated. The time required for the modeling ranged from about 150 hours to 900 hours per building, with an average of 415 hours. Half of this time was spent performing the modeling tuning iterations, and 20% on report writing.

Parametric vs. Interactive Savings

One important factor in the evaluation methodology is that the code Base simulation is derived by "taking out" all of the energy-efficiency measures. As with the Design-phase predictions, "parametric" measure savings are calculated by adding the measure to the Base building rather than subtracting it from the Energy Edge building. These are usually different because of measure interactions. Total "interactive" savings for the whole package of measures is estimated from the difference in energy use for the simulations with (Energy Edge Tuned model) and without (code Tuned Base model) the package of measures. To estimate the energy savings for each measure, the difference between the interactive and parametric savings are prorated among the measures so that the sum of individual measure energy savings is consistent with the entire package. In general, parametric total savings were about 10% greater than interactive, ranging from about 4% less to over 60% greater. This method of accounting for interactive effects differs from more common approaches where measures are ranked and analyzed by order of cost effectiveness.

5.2 Predicted vs. Tuned Results: The Landmark Building

To illustrate how the data are compiled for each of the Tuned buildings, we describe the results for a typical small office. Figures 5.1 and 5.2 show the end-use data and energy savings by measure for the Yakima Landmark building, a two-story, 13.4 kft^2 office in Yakima, Washington[2]. Energy-use intensities from the Design-phase predictions and Tuned models are shown in Figure 5.1 for the Energy Edge and the hypothetical MCS Base buildings. Actual monitored end uses, with heating, ventilation, and air-conditioning (HVAC) as a single end-use, are also shown. Some of the difference between the "Tuned Edge" and "Actual Monitored" end-uses is from variations between site and long-term average weather.

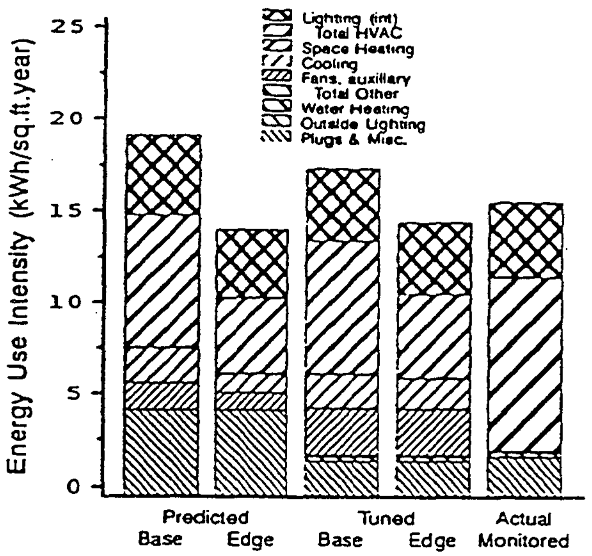


Figure 5.1. Design-phase predicted, Tuned, and Monitored Energy End-Uses for Landmark.

Whole-building energy use comparisons of the Design-phase predicted and Tuned scenarios show a trend for this building that is consistent with the average for all Tuned buildings and for the subset of seven small offices. The Tuned Energy Edge building consumed slightly more than the Design-phase predicted Energy Edge building (14.6 vs. 14.2 kWh/ft^{2}year), but the Tuned Base building consumed less than the Design-phase predicted Base (17.4 vs. 19.1 kWh/ft^{2}year). End uses that differed most from the design-phase predictions are ventilation (160% greater) and plug loads (less than half of predicted). Total "Tuned" energy savings for all measures modeled as an interactive package (2.9 kWh/ft^{2}year) is about half as much as predicted (5.0 kWh/ft^{2}year, see Figure 5.2). The total parametric savings— the sum of the savings for each measure modeled separately against the Base — are slightly less than the interactive total (2.80 kWh/ft^{2}year).

---

[2] Similar figures and associated tables for each Tuned Energy Edge building are included Appendix B.

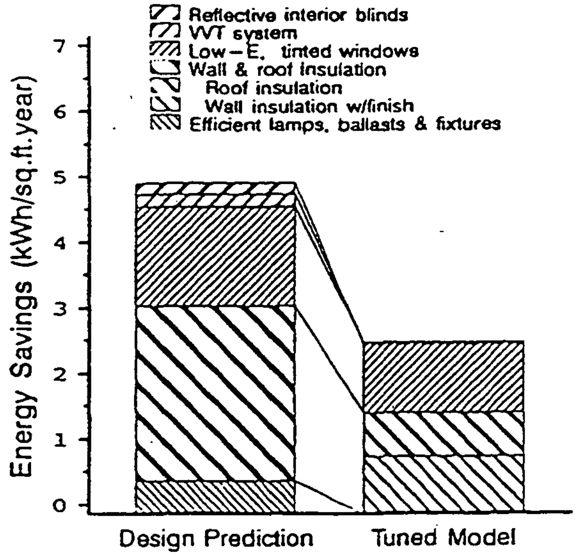


Figure 5.2. Design-phase Predicted and Tuned Measure Savings for Landmark.

At Landmark, the design included lighting, envelope (BPA- and owner-funded), and HVAC measures (Figure 5.2). Only the envelope measures were evaluated in the Tuned model. Tuned measure savings were less than predicted for most of the measures. One factor that contributes to reduced savings from the insulation is that the Design-phase prediction assumed R-6 insulation for the Base wall, but the Tuned model Base wall is R-11. Efficient lighting was not installed, and the power density (1.8 W/ft^2) actually exceeded both the 1985 MCS (1.5 W/ft^2) and the 1986 Washington (1.7 W/ft^2) code. The Variable-Air-Volume, Variable-Temperature (VVT) HVAC system was installed, but later reconsidered as an efficiency improvement because the VVT was not significantly better than a typical constant-volume rooftop unit[3].

5.3 Strengths and Weaknesses of Tuned Models

Calibrated computer models can be an effective means to identify differences between predicted and actual energy use and energy savings. Such models may eventually become the heart of intelligent control systems, operating with an Energy Management and Control System to evaluate energy use trends in real time, with direct feedback to control strategies. At present, however, we are faced with uncertainties since computer simulations are simplified models of real buildings. Model tuning is an extensive, time-consuming exercise and model refinements can be endless. Large scale evaluation programs require lower cost, simplified evaluation methods. An important benefit of model tuning was the continual error checking. Even finished Tuned models contain errors, and the process of comparing simulation output with monitored data allows modelers to continually improve the model.

Future model tuning and measure evaluations should focus on the most important energy issues within a building, rather than giving equal weight to all end-uses. The model tuning and evaluation activities in Energy Edge were oriented toward HVAC measures due to the complexity of the interactions between the building shell, HVAC systems, controls, weather, and schedules. Most non-HVAC end-uses are simpler to model. Water heating, for example, can be modeled simply by knowing the system size, efficiency, and schedule. The complexity of lighting system models depend on the type and regularity of the control system. An accurate representation of the use of daylight in a building can easily reach the complexity of an HVAC model.

---

[3] Most VVT systems are central VVT, not rooftop VVTs and the installed system is not a good example of high efficiency VVT technology, but is a fairly common system type.

One uncertainty in the HVAC simulations is the monitored data have not always been disaggregated by heating, ventilation, and cooling energy use. Further disaggregation could have been derived from the measured data, as described in the Siskiyou heat pump analysis (Piette et al., 1992). The additional detail is useful in evaluating certain HVAC systems. For example, Dubal has electric-resistance heat, which was not disaggregated from total HVAC in the Tuned model. About one-third of the direct annual energy savings of the lighting measures are lost because of the net increase in HVAC energy. With only total HVAC energy we are unable to identify the decreased cooling and increased heating energy use.

Final parting comments from the modelers on their experience with the model tuning methods have been summarized in the "Modeler's Retrospective" (Kaplan Engineering and PECI, 1993). Among several issues listed in the report we repeat three that are particularly relevant:

- "We have more confidence in our building performance modeling than we do in our assessment of individual ECMs."
- "Archiving of models during the different phases (of the project) has been sloppy. Future programs should set up archiving requirements and procedures right up front."
- "Monitoring planning should start with consideration of the HVAC control sequence and consider what measurements are necessary to verify that sequence, at least in the critical energy affecting modes and stages. One-time functional performance (commissioning-type) tests should be considered as an option to continuous measurement. Possibly these tests could be combined with a reduced number of monitored channels to get an indication of the consistency of operation over time."

Baseline Issues

While Energy Edge has explored four methods to calibrate simulation models with measured data, only one approach has been used to define baseline conditions. In the absence of an actual "control" building corresponding to each Energy Edge building, use of a model to simulate energy performance for each measure may seem straightforward. However, it presumes that the input data are sufficiently complete and detailed, and that the simulation adequately represents the building systems to permit proper calibration to monitored data to properly represent each measure. Unfortunately, the monitored data are often insufficient to characterize many of the measures. For example, lighting energy-use data at the circuit level reveal little, if any, information about the performance of occupancy sensors that cover only a small fraction of the power on the monitored circuit.

The difficulty of defining baseline conditions for modeling the performance of an energy-efficiency measures is at the heart of the comment that we have more confidence in our building performance modeling than we do in our assessment of individual measures. The following five questions can be asked to to describe how well the Tuned model captures the performance of an energy-efficiency measure.

- **Is the measure covered in the MCS code?** Many measure characteristics are specifically discussed in the code, such as heat pump efficiencies and lighting power densities. Refrigeration measures, however, are not included in the code. Still others, such as controls like setback thermostats, are discussed, but with ambiguous performance characteristics.
- **Are code compliance calculations necessary?** Some measures require examining several components of a building system in aggregate in order to assess code compliance. Shell measures fall into this category; code compliance may require the calculation of a whole-building UA.
- **Is the baseline system clear and straightforward?** Control measures and building orientation often have this problem.
- **Is DOE-2 modeling straightforward?** Nearly all of the measures can be modeled in DOE-2 (increased spa insulation is one that cannot be). There is, however, a wide range in how adequately DOE-2 can characterize a measure or a building system.
- **Does modeling include information on equivalent levels of service?** DOE-2, like most building simulation programs, is strong at characterizing thermal systems. Generally, both the MCS baseline and energy-efficient HVAC systems provide equivalent levels of climate conditioning. In contrast, the baseline and energy-efficient lighting systems have not been examined to ensure that they would provide comparable lighting levels.

Below are some additional examples of modeling issues for each class of measure.

Shell measures. Shell measures are generally straightforward to model. The use of the Window 3.0 computer program helped to ensure that glass and frame characteristics were considered in the window systems. In a few cases, modeling of shell measures was complicated by code compliance violations[4]. As mentioned, infiltration measures were dropped from the Tuned models because of difficulties in defining baseline conditions.

HVAC measures. Some HVAC measures are straightforward to model and some are problematic. Modeling of economizers requires knowledge of the control settings and damper conditions and many of the dampers were malfunctioning; It is difficult to model such systems since the simulation algorithms assume that the system is properly balanced and operable.

A second example is that modeling of high-efficiency air-to-air heat pumps is generally straightforward, but the model must effectively represent the system's control strategy, as Piette et al., discusses for Siskiyou (1992). Similarly, it was difficult to assess how much electric-resistance heat might have been used with the air-to-air heat pump at Hollywood instead of the ground-source heat pump that did not have resistance heat. The Tuned model concluded there were negative savings for the ground-source heat pump measure.

There were two other instances where the Tuned baseline HVAC system was found to consume less energy than the efficient system. One case was Landmark's VVT system (described above) that was dropped as a measure and not modeled. The other was the Edgerton VAV measure for which the baseline fan-coil system was found to be more efficient[5].

Control measures. Control measures are difficult to model because of the lack of a clear baseline. The 1985 MCS code contains minimal requirements for controls. Provisions for zone, temperature, and setback control are included, but the setback control can be a switch or clock. Timeclock controls are generally considered common practice. However, night-setback control was modeled as a measure at Burger King. Lighting controls are also difficult to model. It is difficult, for example, to estimate the baseline lighting switching patterns that would have been present in areas that were controlled with occupancy sensors. The Tuned modeling of the energy savings from occupancy sensors was based on simple estimates of savings from the MCS code, with little or no information from monitored lighting energy use.

Other measures. Several of the Other measures are not covered in the MCS code, such as refrigeration measures (among the most cost-effective measures in the Energy Edge evaluation). Model savings are based on what would have been built without the Energy Edge project. A survey of common practice would have helped substantiate the baseline assumptions used for measures not included in the code.

Lighting measures. Another factor in how well a measure can be represented within DOE-2 is whether the measure is modeled *directly* or *indirectly.* With **direct modeling** the simulation is used directly to generate the energy savings for a measure. By contrast, **indirect modeling** consists of manipulating key factors exogenously from the simulation, using the model primarily for energy accounting. Most of the HVAC measures are modeled directly: the characteristics of the Energy Edge building are modeled, and compared with a model incorporating baseline HVAC characteristics, such as a change in heat pump COP. The building's indoor comfort requirements are maintained, for both the Base and the Energy Edge model runs, to verify that both systems provide equivalent levels of service.

The lighting measures, however, are modeled indirectly, and equivalent levels of service are not evaluated to ensure that they are held constant. The baseline lighting system is modeled by adjusting the

---

[4] The lack of floor insulation at Thriftway was a code violation, which complicated modeling of the increased roof insulation because the actual overall UA did not meet the code.

[5] The VAV system description, however, is a bit misleading because reheat is normally used to control local zone temperatures when a system both heats and cools. This system only heats. A two-pipe fan-coil Base system was determined to be more energy efficient, but it provides different services than the actual system. The actual building can use 100% outside air for cooling, and the fan-coil system cannot. Therefore, some free cooling is provided in the actual building.

zone lighting power levels to the code power density. For example, in the case of office buildings, the baseline lighting power levels reflect an average power density of 1.5 W/ft^2. The baseline system is modeled using an adjustment factor to account for the change in zonal lighting power, using the simulation program to track the hourly lighting schedule. The simulation also captures interactions between lighting and HVAC systems. However, there is no check to ensure that both the baseline and the Tuned lighting systems provide equivalent lumen output. This difference in modeling suggests the need for alternative evaluation tools for lighting systems[6].

Tuning Period

One aspect of the Tuned models that we examined was the periods of time for which billed and monitored data exist, and the period used in the model tuning. As discussed in Chapter 2, energy use increased over the first several years for most of the buildings and the results of the Tuned models could differ if the tuning period was not representative of stable operation. In most buildings, energy use patterns in the tuning period were quite representative. At Burger King, Eastgate, Evergreen, and Marsing, however, the load climbed during the tuning period. At Tieton the load dropped during the tuning period. At STS and Bellevue the building load during the tuning period was low relative to normal patterns.

Emphasis on Energy and Not Peak Demand Savings

The Energy Edge project has been concerned with energy use and not with maximum peak demands. Maximum peak demands are important in many commercial building analysis because high peak demand charges included in most electricity rate structures can account for more than thirty percent of annual electricity costs. Electric peak demand charges in the Pacific Northwest are low, but growing. Historically the region's electric supply system has peaked in winter mornings, driven by residential heating. As commercial sector cooling loads increase, some utilities are experiencing larger summer peaks. Most of the buildings in Energy Edge are winter peaking, or have similar winter and summer peak demands. Had peak demand been included in the evaluation the Tuned model methodology would have needed to consider calibrating the simulations to peak demand and load shape as well as energy use data.

5.4 Changes from Design-Phase Predictions to Tuned Models

Over 200 different energy-efficiency measures were evaluated in Energy Edge. In several cases, measures installed in the buildings are not evaluated in the Tuned model. There are several reasons why a measure in the Design-phase prediction might not have been evaluated in the Tuned model, or why it is difficult to compare the savings estimates between the two models. Although we do not have definitive explanations for each measure, the following list of reasons for differences are listed in general order of importance.

1. **Different Characteristics of Measure or Building:** Original assumptions were reasonable, but actual building has different conditions, (e.g., longer hours, more people, higher internal gains, different infiltration loads) which influence the energy savings from a measure. For example, if cooling loads are less than predicted, energy savings from economizers may be less than predicted. (These changes have also been the most difficult to track because the assumptions are embedded in the models.) In several cases the specifications of the measure changed, such as the R-value of the insulation or the lighting power density. These changes occurred for both the efficient and the baseline systems.
2. **Measure Was Not Modeled Individually:** Some measures were listed separately but are combined with related measures in the Tuned model. At West Yakima the window tints were modeled with the Low-E windows; the Dryvit was combined with the wall insulation. The savings are therefore accounted for, but impossible to isolate. The aggregations were more common in the Design-phase models.

---

[6] One such tool is LEAR (Lighting Energy Analysis for Retrofit, also applicable to new buildings) which can determine the efficacy, input power, lumen output, and economic feasibility of retrofits (Rubinstein et al., 1991).

3. **Design-phase and Tuned Modeling Techniques Differed:** Early modeling of the measure may have been incorrect or models which were not DOE-2 based may be significantly different from the corresponding Tuned model. The original model may have been unable to characterize the measure, such as the ventilation strategy at McDonald's (Diamond et al., 1992).
4. **Measure Lacked a Baseline:** Certain measures are difficult to model due to the lack of a clearly defined baseline. Control measures are the best example, where the modeler must develop a *poorly* or *loosely* controlled HVAC or lighting system. Infiltration measures, such as the vapor barrier at Siskiyou or the vestibule at East Idaho, were dropped as measures because of the lack of a well-defined baseline.
5. **Measure Malfunctioned:** Measures failed because of poor equipment characteristics, installation, or operating conditions. The Base and Energy Edge model are the same, therefore energy savings are assumed to be zero. The daylighting systems at McDonald's and Siskiyou fall into this category. This may introduce some error, as a malfunctioning measure may have some small savings, or may even consume more energy than if it were not installed at all.
6. **Measure Was Not Installed (or Measure Added):** Not all of the measures in the Design-phase predictions were installed in each building. For example, the efficient lighting systems were not installed at Landmark or West Yakima, and were therefore not included in the Tuned models. In some cases some of the specified efficient lamps were replaced with standard lamps (Director and Dubal Beck). The opposite was true for a few buildings in that measures were installed that were not considered in the prediction. For example, variable speed drives were added to Eastgate after the building was built.

In the interest of exploring low-cost evaluation methodologies it is useful to examine differences between the Design-phase predicted, As-Built, and Tuned models. The As-Built model costs less to develop than a Tuned model because it lacks the energy end-use calibration. The results of the comparison between the different models were mixed. The As-Built models were not better predictors of total energy use than the predicted models for half of the buildings. Overall, As-Built energy-use intensities (EUIs) were not closer to the Tuned EUIs than the Design-phase predicted EUIs were. One factor confounding a comparison of simulation results is the range in abilities and techniques among the modelers. Several different simulation programs were used to develop the predictions, including DOE-2. Even if the modelers had all used DOE-2 there would be variation in their use of the tool. Another trend is that buildings with the lowest predicted EUIs tended to use more than predicted.

5.5 Shortcomings of Data and Uses Beyond Modeling

Below is a summary of how project data were used outside of the model Tuning activities. This discussion includes a description of the shortcomings of the project that leave broader building performance issues unaddressed.

Utility Bill Analysis. One difficulty in evaluating new buildings is the ambiguity of the "start-date". Many buildings, particularly medium and large offices, can take several years to be fully occupied. This fact, coupled with our interest in tracking the persistence of energy savings, led us to carefully track utility bills (Chapter 2). Another reason to analyze bills is to examine how the single year of end-use data used for the model calibration compares to longer term trends for each building. We discussed these data in Chapter 2.

Comparisons of Design-phase Predictions, Tuned, and Measured End-Uses. It is useful to compare these data to evaluate the accuracy of the pre-construction estimates. As discussed in Chapter 2, we found that HVAC energy use was underestimated in most buildings.

Direct Analysis of Monitored Data. Initially, the on-site monitoring was seen exclusively as a source of data for calibrating the models. However, experience has shown that the monitored data can provide direct information on the performance of some conservation measures and useful feedback on the use of models to estimate energy savings. Analysis of the measured data can also provide information on building systems that may not be part of the efficiency measures, such as outside-air fractions in supply air. Other examples include direct analysis of heat pump data (Chapter 3) and analysis of monitored data from the commissioning case study (Chapter 4).

Once the on-site instrumentation were designed, installed, and de-bugged, there was a strategic decision made: should one simply **observe** the building's normal operation over a year or two, or are there instances when it is better to **deliberately intervene** in building or subsystem operation, to test a specific feature or extend the range of conditions available for measurement? A calibrated model can help untangle cause and effect, but in many cases it may be possible to directly monitor the performance of a measure by conducting a controlled test with the help of the monitoring equipment already in place. For example, the contribution of an economizer cycle, heat recovery unit, or lighting controls can be directly tested by alternately enabling and disabling the feature.

In many cases a direct test, rather than continuous end-use monitoring, may have been the best way to determine a measure's impact. For example, a building might be initially monitored with the occupancy sensors installed but disabled, or to signal occupancy to the data logging equipment. After a period of manual switching, the occupancy controls could be connected, and monitoring continued. This approach would probably work best in newly-occupied spaces, or in cases where the building's tenants are changing. In several cases, the original monitoring plan did call for measure-specific tests of this sort, but these were not undertaken.

Analysis of O&M Audits and Characteristics Data. Throughout the analysis we have sought to use building characteristics data to explain energy consumption trends. Unfortunately, tracking these data has been difficult, complicated by conflicting and insufficient information on assumptions used in models and the lack of detail regarding actual building systems because of inaccurate and incomplete building audits. We experienced a great deal of difficulty in extracting even basic facts about installed measures, building features, conditioned floor area, and estimated costs and savings.

A review of the problems with many of the efficiency measures is presented in Chapter 4. The audits omitted some important elements - such as a log of important energy-related events at each site that may occur between audit visits. For example, the O&M audit format did not include questions about equipment breakdowns, control problems, or other significant operating events between site visits. To complement the periodic O&M visits, building operators should have been encouraged to keep event-logs between O&M visits. Several of the sponsors who oversaw the audits commented that they did not know the audits would be used in the evaluation to gather ongoing building operating data (rather they thought the audits were to assist in compiling information for model tuning only).

Comparison Buildings Approach. Chapter 2 contained a review of regional comparison buildings data to provide context for evaluating overall trends in energy use among the Energy Edge buildings. These comparisons show that most of the Energy Edge office buildings are low-energy buildings for all three end uses (HVAC, interior lighting, and other). The comparisons are most robust for small offices where the most complete characteristics data are available to better understand the samples being compared and the sample sizes are larger than for other building types. However, since the sample sizes are limited, we must be cautious in making any generalizations.

Building Services: Comfort, Air-Quality, etc. Surveys of occupant satisfaction were conducted in seven Energy Edge buildings, as described in Section 2.5. However, there is a general need for more attention to "output indicators" of the level and quality of energy services actually delivered to building occupants. To be valid and complete, measures of energy performance must not look at only one side of the equation—the amount of energy used—while ignoring the **output** side. This is most obvious for thermal comfort conditions, which are often simply assumed to meet design specifications, or in some cases (as with the Energy Edge buildings) partly monitored using air temperature and humidity as indicators. Similar issues apply to: the quality of the lighting environment (given the visual tasks being performed), indoor air quality, acoustical characteristics, and other measurable or hard-to-measure variables which together represent the quality of energy services delivered by the building and its mechanical systems.

5.6 Alternative Evaluation Methods

Any program of investment in energy supply or efficiency requires methods to verify and to measure its performance. In Energy Edge, it has been important to determine the savings for each measure, and each building. BPA is currently planning the evaluation for the full-scale Energy Smart Design (ESD) program. The success of this program will be measured on an aggregate basis, requiring significantly different evaluation methods from those used in the Energy Edge project. The data in the Energy Edge evaluation are far more detailed than most evaluation efforts have access to or can afford. These data have been used to examine simplified alternative evaluation methodologies to help future efforts, as described below. Energy Edge data were also used to explore a sophisticated evaluation tool knows as Equivalent Thermal Parameters, also described below.

Evaluating Savings with EUI Adjustments

During 1991, BPA proposed a method to evaluate energy savings by calculating the ratio of the actual whole-building energy use (from utility bills) to the Design-phase predicted total energy use. This factor is then multiplied by the savings predictions for each measure to adjust the savings estimates using measured results. The concept was that if energy use increased from the design-estimate, energy savings probably also increased. Thus,

$$Savings_{estimate}(kWh/yr) = Design{-}phaseSavings_{prediction}(kWh/yr)\frac{Whole{-}Building_{actual}(kWh/yr)}{Whole{-}Building_{prediction}(kWh/yr)}$$

This method assumes that building efficiency is constant and that changes in energy use are determined by changes in the amount of use, e.g., hours of occupancy.

Another method is to assume the opposite, that is, that amount of use is constant, and that energy use variations are explained by changes in efficiency. This method uses the same formula except that the adjustment factor is predicted over actual rather than actual over predicted—the exact inverse. That is, in one case, the fact that a building uses more energy than predicted is taken to mean that more energy is being saved, and in the other case, more energy use implies less energy is saved. In reality, both effects occur, which is why the estimation task is so difficult.

Both methods are misleading. For example, at West Yakima, while the energy use of the actual building increased compared to the Design-phase prediction (by about 54%), the Tuned model showed decreased total savings (only 31% of the original savings estimate). Applying an EUI adjustment to the Design-phase predicted savings results in a poorer estimate of the Tuned savings than the predicted savings themselves.

Equivalent Thermal Parameters

As an adjunct to the analysis of measure savings in the Energy Edge project, some effort was expended continuing the development a new procedure for empirically calibrating a simple, lumped-parameter simulation model to the hourly time-series metered data. This model is termed ETP, for Equivalent Thermal Parameters (Pratt and Taylor, 1994). The Bonneville Power Administration has made extensive use of metered end-use data as a key element of many of its evaluation and research projects (e.g. Hood River, Residential Standards Demonstration Program, End-Use Load and Consumer Assessment Program, as well as Energy Edge). However, the sheer volume and complexity of the data makes it difficult to estimate efficiency measure impacts or even determine whether the buildings are operating as they should, using purely empirical analysis techniques.

In the commercial sector, engineering simulation models calibrated to the metered data are useful, as illustrated by the Energy Edge project. Their usefulness stems from the fact that they compute heating and cooling loads based on well known heat transfer principles. Therefore, seeking to modify these principles is not the intended function of ETP, nor is it likely that the simulations have gross errors in their application. In many applications, such as design tradeoffs being considered for buildings not yet constructed, there is no way to analyze their impacts other than bottom-up simulation. ETP is not intended as a replacement for bottom-up simulations for these important applications.

However, traditional engineering simulation models are not easily calibrated to metered data for a number of reasons. Further, the high precision with which they account for energy using these principles does not necessarily result in highly accurate estimates of conservation measure impacts in real-world buildings. Where consumption is incorrectly attributed by the simulation analysis to one attribute of the building (at the expense of another), predictions of savings from the conservation measures involved them will necessarily be in error. Such errors tend to result from incorrect judgements on the part of the analyst or from incorrect or unrealistic assumptions embedded in the simulation itself. The desire to understand the magnitude and nature of these errors led to efforts to collect metered end-use data and drives the need for models like ETP.

Given the time, expense, and uncertainty of the MCT-tuned model calibrations to the monthly metered end-use data that forms the backbone of the Energy Edge analysis, it is clearly desirable to have procedures that can identify key thermal characteristics such as heat loss rates, ventilation flow rates, and HVAC system efficiencies and create a simulation model that matches the hourly pattern of loads. The ETP approach is designed to provide a means of analyzing such data in a modeling framework that has an easily interpretable physical meaning, so that the mass of available data can be put into meaningful terms for analyzing these issues.

For these reasons, it was decided to pursue a small exploratory effort to apply the ETP technique for analysis of Energy Edge data. This involved advancing the development of the ETP model beyond the proof-of-concept stage (it had only undergone controlled tested using end-use "data" generated by DOE-2) so it could be applied with actual data collected in the field.

The importance of such procedures is highlighted by the results of the STEM-based DOE-2 calibration, conducted for a few Energy Edge buildings. The STEM procedure, based on adjusting primary parameters of the DOE-2 simulation model to match data from a series of short-term tests (over a period of a few days) resulted in a conductive heat loss rate for the East Idaho Credit Union building that was only 43% of the engineering estimate used in the MCT-tuned model, raising a degree of uncertainty about the Energy Edge analysis procedure and results. Therefore, it was decided to apply the experimental ETP procedure to the long-term metered end-use data for East Idaho Credit Union to see how the heat loss rates estimated by it compared.

Table 5.1 compares the heat loss rates per unit temperature difference (Btu/hr-°F) for the two primary zones of the East Idaho Credit Union as calculated for the MCT-tuned model and as estimated by the ETP procedure for the period 12-20-1990 through 5-31-1990. Also shown are the STEM-tuned heat loss rates for the two zones, although the STEM procedure was conducted for the whole building and so does not differentiate the overall adjustment factor determined (0.425) on a zone-by-zone or a component-by-component basis.

Table 5.1. Comparison of Heat Loss Rates from MCT-Tuned, STEM-Tuned, and ETP Models for East Idaho Credit Union.

Zone	Component	MCT-Tuned (Btu/hour°F)	STEM-Tuned (Btu/hr-°F)	ETP-Tuned (Btu/hr-°F)
2	Conduction	124	53	
	Conduction*	22	9	
	Slab**	54	23	
	Infiltration (const.)	48	48	
	Subtotal	248	133	202
	Infiltration (10 mph wind)	38	38	58
	TOTAL	286	171	260
	Conduction*	12	5	
	Infiltration (const.)	36	15	
	Subtotal	164	70	198
	Infiltration (10 mph wind)	30	30	35
	TOTAL	194	100	233

* Conduction to unheated attic space; actual heat loss will be slightly smaller

** Slab shown separately because DOE-2 modeled it as an underground surface, with significant uncertainty about it's true engineering heat loss rate to the outdoors

The ETP results agree remarkably well with the engineering assumptions in the MCT-Tuned model, differing by only 10-15% and without a consistent bias. This result generally supports the accuracy of the engineering assumptions about heat loss rates embedded in the MCT-tuning process, although the ETP procedure remains experimental.

The ETP procedures for Zones 2 and 4 (the first floor) resulted in regressions with very high R^2, (explaining 0.984 and 0.989 of the variance, respectively). The Zone 2 results were obtained using periods of nighttime temperature decay, with the lights, plugs, and baseboard heaters serving as a reference heat source. This procedure has been extensively tested and refined in the ETP development process. Zone 4 results were obtained using heating loads at night and on weekends, when the building was unoccupied and the thermostat was set-back, because lighting and plug loads at night were insufficiently large to serve as a known heat source. Thus, the ETP procedure used for Zone 4 uses the backup resistance heat from the packaged HVAC unit combined with the lights and plugs as it's known heating source. On this basis, the model for Zone 4 also produced estimates for the average operating heat pump COP (2.7) and ventilation flow rate 100 ft^3/min (7.5% of rated total flow rate 1353 ft^3/min) that agreed well with MCT-tuned modeling assumptions. The procedure used for Zone 4 has not been rigorously tested or refined, however it appears to give good results. Statistical uncertainties in the ETP results are reflected by standard errors of about 3% and 15% for the heat loss rates, and 8% and 20% for the wind-induced infiltration components in Zones 2 and 4, respectively.

Simplifying Data Collection

Review of the end-use load shapes has indicated that, as expected, many of the end-uses are extremely regular, driven by equipment or occupancy schedules. Exterior lighting is perhaps the best example. As an alternative to 8760 hours of metered data, two weeks of winter and summer operation coupled with periodic audits may be sufficient to characterize a predictable end use such as exterior lighting. This alternative is especially important if the end-use is not directly related to the measures. Service water heating is another small end use that we found to be relatively constant. One drawback to this method is that it may be less likely to catch equipment failure, or uncover unexpected changes from normal functioning.

Using Energy Management Control Systems for Performance Analysis

An Energy Management and Control System (EMCS) is a computer-based electronic system for controlling HVAC and/or lighting systems. The major components of an EMCS are sensor inputs, actuator outputs, and a processor to calculate the appropriate control responses to the inputs. The inputs, outputs, and certain intermediate values are often referred to as "points".

EMCSs can play several different roles in monitoring building performance. This section outlines these roles, discusses recent work on using EMCSs as a monitoring tool, and describes the EMCSs in one of the Energy Edge office buildings. Appendix A5 includes a description of the EMCS characteristics and problems encountered with the EMCS's operation for other large offices (also discussed in Heinemeier, 1993).

Seven Energy Edge buildings have EMCSs, five of which are large office buildings. By studying how these systems were used or could have been used, we were able to learn about what changes could be made to enable these systems to become more powerful tools. Our investigation supports the findings from other recent work (see Heinemeier and Akbari 1993).

The first limitation is that most EMCSs have not been programmed for extensive data monitoring, and they are not sufficiently flexible to be easily reprogrammed. This often makes them inconvenient for monitoring. For example, at the EPUD building, a customized translation box had to be built, as further described below. Serious consideration was given to configuring a computer to mimic a printer at the Montgomery building. Data collection capabilities would be greatly enhanced with relatively small changes in system design, such as creating concise and consistent formats for requesting and reporting data, ensuring that data were averaged and reported reliably over an hourly interval, and creating a simple means of rapidly displaying or transmitting the data.

Secondly, each site must be evaluated individually. It is difficult to generalize on EMCS capabilities, due to differences in model characteristics, installed functions, and the degree of system utilization. The EMCSs in Energy Edge buildings reflect this and vary widely. It is also often difficult to assess EMCS capabilities, because the EMCS operator typically lacks the information, resources, and incentives to assist the assessment. To address this difficulty, a set of guidelines has been drafted to aid the building researcher in evaluating the use of EMCS for monitoring, and for carrying out that monitoring (Heinemeier and Akbari 1992).

Thirdly, there are often O&M problems with the EMCS itself, which can affect its ability to collect data. In the Energy Edge buildings studied, there were problems with sensor location and calibration, improper and excessively complex programming, disabled daylighting controls, overridden heat pump scheduling, and equipment not controlled by the EMCS as originally anticipated. These issues confirm the importance of commissioning EMCSs, especially if it is to be used for monitoring building performance.

Since EMCSs have the potential to be powerful tools in projects such as Energy Edge or Energy Smart Design, further developments in the capabilities of EMCSs could be followed and possibly influenced. Definition of a standard protocol for EMCS monitoring could help drive future EMCSs to be more readily useful in such programs.

Emerald People's Utility District Headquarters (EPUD). EPUD is the only building where the EMCS was used with the data acquisition system to assist in the building monitoring. EPUD has a Barber Colman EMCS, used for control of lighting, HVAC, and emergency functions (not a BPA-funded measure).

A number of problems with the EMCS were identified in the O&M audits. The programming was too complex, with the software consisting of over 100 separate programs, written in a custom computer language, which the building personnel and the controls contractor have trouble understanding. Several control failures were encountered and corrected during the first year, and building personnel have disabled several capabilities, particularly those relating to daylighting controls.

Twenty-three EMCS sensors were used as inputs in the Energy Edge monitoring; three duct temperatures, six zone temperatures, seven mass temperatures, four cement-core-flush temperatures (for structural thermal storage) and three lighting levels. The data logger tapped directly into some of these sensors. One drawback of this approach is that wires had to be run out to the zone sensors, adding to the expense and the intrusiveness of the monitoring project. A custom-engineered translator box was used as an interface between the EMCS and the Energy Edge logger. This box tapped into the communications bus, acting like a modem on one of the ports. The translator box involved sophisticated engineering, and was relatively expensive. The box translated from the proprietary EMCS communications protocol, to the protocol used by the Energy Edge logger. Once the data were collected by the logger, they were in a format consistent with other Energy Edge data. The Energy Edge monitoring contractor said that this method was "not recommended," and that, had it been a possibility to run wires, it would probably have been less expensive to install their own sensors. The control system malfunctioned at one point, and in the process of fixing it, was changed to use a new protocol, so that a completely new box had to be built.

During infiltration and cool-down tests described in Subbarao (1993) the EMCS was used to collect data. Figure 5.3. shows the output of a mass temperature sensor from data collected by the Oregon Department of Energy. EMCS-derived data were also used in Short-Term Energy Monitoring (STEM) tests performed on this building (Subbarao, 1993).

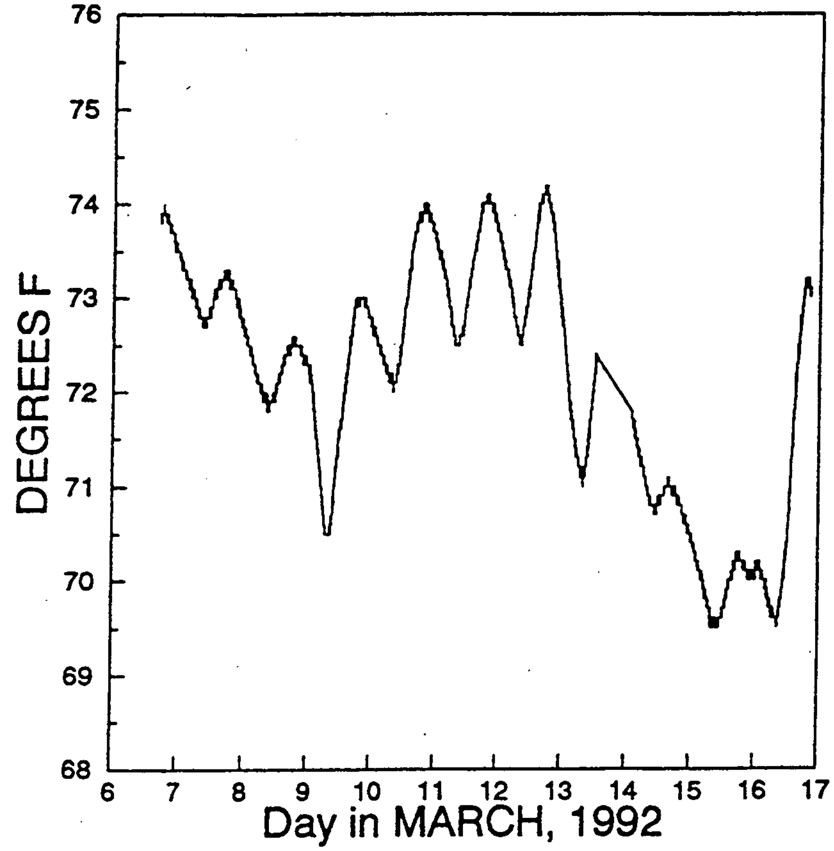


Figure 5.3. Data collected at EPUD during cool-down tests. This mass sensor was embedded in the fin wall of the north-west zone of the building. Several mass temperature sensors were part of the EMCS equipment and were accessed for Energy Edge monitoring, as well as other efforts such as this cool-down test and STEM testing.

5.7 Comparison with the ESD Prescriptive Path

The Energy Smart Design Prescriptive Path is a simplified method to specify energy-efficiency measures for small commercial buildings under 15 kft^2. To obtain incentive payments for energy-efficiency measures large buildings must perform simulations of the measures. Small buildings can follow the Prescriptive Path method to evaluate measures with a "cook-book" approach. We have conducted a brief comparison of the performance of measures from the Prescriptive Path with Energy Edge results to provide program planners and evaluators an indication of major differences.

The energy savings estimates and cost-effectiveness of measures in the Prescriptive Path were developed by Brown and Caldwell (1990) with a series of DOE-2 simulations. The modeling covered several groups of conservation measures to examine changes in energy end-use estimates for three different climate zones and seven building types: for offices, retail stores, theaters, churches, restaurants, motels, and warehouses. GPP Comparing the Prescriptive Path simulation results for the small offices with the Energy Edge small offices, the building type for which we have the most complete information, shows several differences. First, we found that the baseline energy use is higher in the Prescriptive Path modeling than the baselines used in the Energy Edge Tuned models. The Prescriptive Path small office baselines use between 18.0 and 21.5 kWh/ft^2-year for the three climate zones. These EUIs are more similar to the comparison building EUIs described in Chapter 2. The average Design-phase predicted Base for the seven Tuned small offices in Energy Edge was 15.9 kWh/ft^2-year, and the average Tuned Base was even lower at 14.0 kWh/ft^2-year (Figure 2.4).

A second significant difference between the performance of the energy-saving measures in Energy Edge compare to the Prescriptive Path is that the costs for the measures are higher in Energy Edge for comparable measures. For example, the Prescriptive Path estimates for efficient lighting systems (\$0.29/ft^2) economizers (\$0.19/ft^2), and windows (\$0.50/ft^2 for the 0.33 Btu/hr-ft^2-°F window) are less than half of the averages for comparable measures (discussed in Chapter 3, Figures 3.3, 3.4, and 3.6).

A third point is that the actual EUIs for the small offices in Energy Edge are lower than the EUIs derived from the Prescriptive Path for buildings with the most aggressive set of efficiency measures. The lowest achievable EUIs from the Prescriptive Path simulations for the three climate zones are between 12 and 14 kWh/ft^2-year. All eight of the Energy Edge small offices use 14 kWh/ft^2-year or less (see Table 1.1).

Finally, the costs per kWh saved for the measures in the the Prescriptive Path modeling were lower than the Energy Edge Tuned models. This is because the measures saved more energy than the Energy Edge Tuned models indicated, plus the costs for the measures were higher in Energy Edge. These results suggest that the assumptions used to model the Prescriptive Path measures should be revisited to examine how they differ from the Energy Edge buildings.

Chapter 6. Bibliography

ADM Associates, Inc., "Primary Documentation for the Pacific Northwest Non-Residential/ Commercial Energy Consumption Survey (PNNonRES), Data Management Plan for Phase II," Report to BPA under contract DE-AC79-85BP23671, February, 1992.

Benner, N. and Bjornskov, D., "What is Commissioning and How Much Does it Cost?" *Proceedings of the National Conference on Building Commissioning, prepared by the Portland Energy Conservation, Inc., April, 1993.*

BR Associates, Inc., "Primary Documentation for the Pacific Northwest Non-Residential/ Commercial Energy Consumption Survey (PNNonRES), Volume 5: Analyst's Guide to PNNonRES," Report to BPA under contract DE-AC79-90BP10392, February, 1992.

Brown and Caldwell, "Summary Report for the Prescriptive Path Manual Project," Report for BPA, June 1990.

Diamond, R.C., Harris, J.P., deBuen, O., Nordman, B., "Evaluating Actual Performance of New Commercial Buildings: The Energy Edge Demonstration Program. *Proceedings* of the 1990 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Pacific Grove, CA, August 1990. Lawrence Berkeley Laboratory Report, LBL-29212.

Diamond, R.C., Harris, J.P., Piette, M.A., de Buen, O. and Nordman, B., "Energy Edge Impact Evaluation: Early Overview." Lawrence Berkeley Laboratory Report, LBL-30711. Prepared for the Bonneville Power Administration, December, 1990.

Diamond, R.C., Harris, J.P., Piette, M.A., de Buen, O. and Nordman, B., "Energy Edge Impact Evaluation: Middle Overview." Lawrence Berkeley Laboratory Report, LBL-32764. Prepared for the Bonneville Power Administration, May, 1992.

Diamond, R.C., Piette, M.A., Nordman, deBuen, O., B., Harris, J.P., Cody, B., "The Performance of The Energy Edge Buildings: Energy Use and Savings", *Proceedings* of the 1992 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Pacific Grove, CA, August 1992.

Fels, M.F., and Keating, K.M, "Measurement of Energy Savings from Demand-Side Management Programs in U.S. Electric Utilities," *Annual Review of Energy and the Environment,* Vol. 18, pp. 57-88, 1993.

Gardner, C.M., and Lambert, L.A., "Monitoring Methodology for Energy Edge." *ASHRAE Transactions,* 87-18-3, January 1987.

Harris J.P., Diamond R.C,. de Buen O., Hatcher A., Nordman B, Piette M.A., "Energy Edge Impact Evaluation: Findings and Recommendations from the Phase One Evaluation," Lawrence Berkeley Laboratory LBL-30358, 1990. Prepared for the Bonneville Power Administration, May 1990.

Heerwagen, J., et al., "Energy Edge Post-Occupancy Evaluation Project, Final Report," prepared for the Bonneville Power Administration, October 1991.

Heerwagen, J., Loveland, J., and Diamond, R.C., "People, Comfort and Environmental Satisfaction in Energy-Efficient Buildings." *Proceedings,* of the 1991 International Solar Energy Conference, Denver, CO, August 1991.

Heinemeier, K.E., "The Use of EMCS in Building Monitoring: Experience from Energy Edge and LoanSTAR Programs." *Proceedings of the National Conference on Building Commissioning.* Portland Energy Conservation, Inc, Portland, OR, 1993.

Heinemeier, K.E., and Akbari, H., *Energy Management and Control Systems and their Use for Performance Monitoring in the LoanSTAR Program.* Prepared for the Texas Governor's Energy Office. LBL-33114, Lawrence Berkeley Laboratory, Berkeley, CA, 1993.

Heinemeier, K.E., and Akbari, H., "Proposed Guidelines for Using Energy Management and Control Systems for Performance Monitoring." *Proceedings from the American Council for an* Energy-Efficient Economy 1992 Summer Study on Energy Efficiency in Buildings. Vol. 3, pp. 3.111-3.120, August 1992.

Kaplan Engineering, "Guidelines for Energy Simulations of Commercial Buildings." Prepared for BPA, DOE/BP-26683-2. Portland, OR, March, 1992.

Kaplan Engineering, "Energy Edge Pilot Study." Prepared for Bonneville Power Administration, September 1989.

Kaplan, M.B., Jones, B., Jansen, J., "DOE-2.1C Model Calibration with Monitored End-use Data." *Proceedings* of the American Council for an Energy Efficient Economy, 1990 Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 1990.

Kaplan Engineering and Portland Energy Conservation, Inc. (PECI), "Energy Edge Simulation Tuning Methodologies," Prepared for the Bonneville Power Administration, March 1992.

Kaplan Engineering and Portland Energy Conservation, Inc. (PECI), "Model Tuning Final Report, Modeler's Retrospective, Energy Edge" Prepared for the Bonneville Power Administration, December 1993.

Katz, G., Baylon, D., Heller, J., and Heidell, J., "Major Projects Rule Phase II Evaluation," Prepared by Momentum Engineering, Ecotope, Inc., and Synergic Resources Corp. for Seattle City Light, Contract Number C87-325, December, 1989.

Kennedy, M. and Baylon, D. "Energy Savings of Commercial Code Compliance in Washington and Oregon," Report to BPA. Portland, OR, by Ecotope, Seattle, WA, August 1992.

Miller, W., Vogt, S., Vincent, G., Perry, J., Anderson, K, Caan, G., "Lessons Learned from the Energy Edge Project for New Commercial Buildings." *Proceedings* of the 1990 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Pacific Grove, CA, August 1990.

Nordman, B. and Meier, A., "Outdoor-Indoor Temperature Relationships," *Proceedings of the ACEEE 1988 Summer Study on Energy Efficiency in Buildings,* Vol. 10, pp. 10.174-10.187, August 1988.

Northwest Power Planning Council, "Northwest Conservation and Electric Power Plan," Portland, OR, Vol. 2, Part 1, 1991.

Northwest Power Planning Council, "Model conservation standards equivalent code," February 1985.

Piette, M.A., Harris, J.P., Diamond, R.C., Nordman, B., de Buen, O., Cody, B., "Evaluating Savings from Design Predictions through Measured Performance in New, Energy-Efficient Commercial Buildings." *Proceedings* of the 5th International Energy Program Evaluation Conference, Argonne, IL, September 1991.

Piette, M.A, deBuen, O., and Nordman, B., 1992, "Energy Performance of Heat Pumps in New Commercial Buildings in the Pacific Northwest," *ASHRAE Transactions,* Vol. 98, Part 2, pp. 352-362, Paper BA-92-3-2, June, 1992, LBL-32451.

Piette, M.A., Diamond, R.C., Nordman, B., de Buen, O., Cody, B., "Predicted Versus Monitored Performance of Energy-Efficiency Measures in New Commercial Buildings from Energy Edge," *Proceedings* of the 6th International Energy Program Evaluation Conference, Argonne, IL, August 1993.

Portland Energy Conservation Incorporated (PECI), *Building Commissioning Guidelines, Second Edition,* Report to BPA, November 1992.

Portland Energy Conservation Incorporated (PECI), *Director Building Final Commissioning Report: Energy Edge Program, Documents 1 and 2,* Report to BPA, February, 1993.

Pratt, R., and Taylor, Z.T., "Development and Testing of an Equivalent Thermal Parameter Model of Commercial Buildings from Time-Series End-Use Data," Prepared by Pacific Northwest Laboratory (Richland, WA), for BPA, 1994.

Rubinstein, F., Zhang, C., and Franconi, E., "1991 LEAR Beta Version 1.0, Lighting Energy Analysis for Retrofits," Lawrence Berkeley Laboratory, October 1991.

Schiller, G., and Arens, E., "Thermal Comfort in Office Buildings" *ASHRAE Journal,* October, 1988, pp. 26-32.

SBW Consulting, Inc., "Analysis of Commercial Model Conservation Standards Study," prepared for the Bonneville Power Administration, November 1990.

Subbarao, K. "Evaluation of the Performance of a Building," final report, prepared for the Bonneville Power prepared for the Bonneville Power Administration, March, 1993. (Evaluation of the Emerald People's Utility District Headquarters (EPUD) building.)

Taylor, Z.T. and Pratt, R.G., "Description of Electric Energy Use in the Pacific Northwest," DOE/BP-13795-22, Bonneville Power Administration, Portland, Oregon. December 1989.

U.S. Bureau of the Census, *Statistical Abstract of the United States: 1992,* 112th edition, Washington, DC, 1992.

Weijo, R., Ponsness, J., and Anderson, K "Prescriptive Path Manual Strategy Sets for Small Commercial Construction Market," *Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency in Buildings* Volume 5, pp. 5.241-5.248, August, 1992.

Yoder, R. and Kaplan, M., "Building Commissioning for Demand-Side Resource Acquisition Programs," *Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency in Buildings* Vol. 5, August 1992.

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098