LBL-36448
UC-1600

Commissioning of Energy-Efficiency Measures: Costs and Benefits for 16 Buildings*

Mary Ann Piette, Bruce Nordman, and Steve Greenberg

Lawrence Berkeley Laboratory
Energy and Environment Division
Energy Analysis Program
University of California
Berkeley, California, 94720

April 1995

Prepared for the Bonneville Power Administration

---

*This work was jointly supported by the Assistant Secretary for Energy-Efficiency and Renewable Energy, Office of Building Technologies, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and the Bonneville Power Administration.

Table of Contents

Acknowledgements

We would like to thank the following people for their support and assistance in this effort: Corinn Castro, Bruce Cody and Alan Grill (BPA), Mike Kaplan (Kaplan Engineering), and Rachel Yoder (PacifiCorp). Valuable comments were provided by Max Sherman (LBL) and Kristin Heinemeier. This work was jointly supported by the Assistant Secretary for Energy-Efficiency and Renewable Energy, Office of Building Technologies, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and the Bonneville Power Administration.

Executive Summary

Introduction

Building systems and energy-efficiency measures (EEMs) often don't perform as well in practice as expected at the design stage. One of the most beneficial periods to intervene in the building life cycle is during start-up. Building commissioning, which involves tests to advance a system from static installation to full working order, is such an intervention. This report examines the costs and benefits of utility funded commissioning in 16 commercial buildings. The broad goal of this study is to improve understanding of the value of commissioning and its potential for enhancing commercial energy-efficiency programs and policies. Half of the buildings are offices and the building types are mixed. The case studies are from a larger sample of over 75 buildings that participated in a utility funded commissioning program in the Pacific Northwest.

Methodology

The costs for the energy-efficiency measures and commissioning were compared with the estimates of energy savings for each measure, and the savings from correcting deficiences found during commissioning. An important part of the methodology was to evaluate how the deficiences related to the energy savings estimates for the EEMs. We defined three categories of relationships: directly related to the EEM, indirectly related to the EEM, and unrelated to or beyond the EEM. We developed estimates of the energy savings from commissioning using a combination of engineering estimates, monitored data, and simulations.

A variety of parameters were developed to examine the cost-effectiveness of commissioning based on typical energy prices for all 16 buildings. To address the uncertainty associated with the persistence of savings from commissioning we included low and high lifetimes in the cost-benefit analysis. Non-energy benefits of deficiency corrections were tracked according to four primary categories of improvements: control, operations and maintenance (O&M), indoor-environmental quality, and equipment life.

Results

A total of 46 dynamic EEMs were commissioned for all 16 buildings and 73 deficiences were corrected. On average, commissioning was marginally cost effective on energy savings alone, although the results were mixed among all 16 buildings. Although we did not quantify the economic value of the savings from the non-energy benefits (except for two examples), it is likely that these benefits were often greater than the energy savings.

Energy Savings

Energy savings estimates were developed for 36 of the corrections; the savings from commissioning ranged from zero to 4.4 kWh/ft^2-year, with an average of 1 kWh/ft^2-year. These savings are equivalent to about one-fourth of the predicted savings from the EEMs although some of the savings were not directly related to the EEM. Our estimates of energy savings are conservative because we only quantified the energy savings from deficiency corrections that were noted in the commissioning documentation as being corrected. It is likely that there were additional energy savings from identifying and correcting deficiencies that were not well documented.

Non-Energy Benefits

Correcting deficiences can make tremendous improvements in a building performance that go beyond energy savings. These savings are difficult to quantify. We tracked non-energy benefits of 64 deficiency corrections. Non-energy benefits were categorized as improvements in control, operations and maintenance, and indoor environmental quality (e.g., noise, comfort, and air quality), and lengthened equipment life. For example, correcting blocked ducts and inoperable thermostats help improve air quality and comfort. Commissioning of large control systems is particularly important. If an Energy Management and Control System (EMCS) is not well commissioned, a building operator may not trust the data for control and scheduling changes. This may cause him to override it, therefore rendering it useless, or at least, much less useful than optimal.

Cost-Effectiveness

Cost effectiveness was evaluated in two ways: considering commissioning as a stand-alone measure, and considering the costs and benefits of commissioning in combination with the measures. Economic parameters included simple payback times and cost benefit ratios using the present value of the energy savings (considering two correction lifetimes).

To estimate the payback time for commissioning as a stand-alone activity independent of the EEMs we compare the cost for commissioning with the total savings from all of the deficiency corrections. The costs for commissioning ranged from \$0.08/ft^2 to \$0.64/ft^2 with an average of \$0.23/ft^2 for all 16 buildings. The average simple payback time was 13.7 years and the median was 6.5 years. Four buildings had payback times less than two years.

To estimate the payback time for commissioning combined with the EEMs we compare the total cost for commissioning and the EEMs with the savings from commissioning and the EEMs. The total costs for commissioning and the dynamic EEMs ranged from \$0.74/ft^2 to \$17.0/ft^2 with an average of \$4.5/ft^2 per building. The total savings assume that once commissioned, the EEM saved 100 percent of the design estimate, plus additional savings from correcting deficiencies that were not related to the EEMs. Under these assumptions the average and median simple payback times are 9.6 and 9.9 years. These results are dominated by the economics of the EEMs.

The economics are sensitive to the assumption of how long the savings persist. The cost-benefit analysis of commissioning as a stand-alone measure showed that benefits are greater than the costs for six of the 16 buildings for the low lifetime scenario. Under the high lifetime case the benefits are greater than the costs at ten of the 16 sites. When considering the costs and benefits of commissioning and the EEMs combined, the benefits exceed the costs for ten buildings for both the low and high lifetime case.

Implications

This study has shown that for most buildings, the investment in commissioning was cost effective based on energy savings alone. Energy prices are low in the Pacific Northwest, and the cost-effectiveness would be higher in other regions of the U.S. The findings are subject to significant uncertainty because of the small sample size and lack of metered data in the evaluation; additional case study analysis is needed. However, the finding suggests that utility sponsored commissioning should be considered in demand-side management activities. In an era when utilities and energy providers are positioning themselves for a deregulated energy marketplace, companies that offer performance assurance and commissioning are likely to be at an advantage because of their more direct involvement in understanding and addressing customer's needs.

Building owners want buildings that work as intended, are comfortable, healthy, and efficient. Looking beyond energy savings benefits, it is likely that the non-energy benefits outweighed the costs at the several of the sites. The owners are generally not well informed, however, about the benefits of commissioning.

The distinction between EEM and whole-building commissioning was blurred, especially among the large buildings. This suggests the need to commission not only the most energy-saving EEMs, but the most energy-consuming building systems. Greater use of metering, Energy-Management and Control System trend-logs, and enhanced links to O&M will help improve the effectiveness of commissioning by increasing the ability to evaluate its value and ensure persistence of savings from deficiency corrections.

1. Introduction

Background

Building systems and energy-efficiency measures (EEMs) often don't perform as well in practice as expected at the design stage. This fact has become clear to many organizations concerned with ensuring building performance. What to do about these problems is less clear. Several electric utilities around the U.S. have begun to take action to address the start-up, control, and operational problems that are found in nearly every building (PECI, 1994). One of the most beneficial periods to intervene in the building life cycle is during the start-up phase of a new building. Building commissioning during start up is such an intervention. **Commissioning** can be defined as:

> a set of procedures, responsibilities, and methods to advance a system from static installation to full working order in accordance with design intent (Yoder and Kaplan, 1992).

In broad terms, commissioning can extend from design reviews through operations and maintenance planning and training. With such a broad scope aimed at the entire building life cycle, commissioning is often likened to "Total Quality Management." Yet the heart of commissioning are the procedures developed and executed to ensure that all building systems function as intended. The incorporation of energy-efficiency criteria into building commissioning is a new development.

This report examines the costs and benefits of utility funded commissioning in 16 new commercial buildings. All of the buildings were part of PacifiCorp's Energy FinAnswer program. Among the hand full of utility commissioning programs currently underway or in development, PacifiCorp's commissioning program is by far the most broad and aggressive in the U.S. Over 75 buildings have participated in the program.

PacifiCorp developed their commissioning program as a result of direct experience with the energy performance of energy-efficiency improvements in new commercial buildings. The utility worked with the Bonneville Power Administration to administer a research-oriented new commercial construction and demonstration project called Energy Edge (Yoder and Kaplan, 1992, Piette et al., 1994). Energy Edge was perhaps the most detailed evaluation of EEMs in new commercial buildings ever conducted. The Energy Edge buildings were not commissioned, and therefore many of the 200 EEMs tracked in the program did not perform as well as expected. Most of the problems with the EEMs could have been prevented or corrected with commissioning. In 1991 PacifiCorp began to offer direct financial payment for commissioning. These incentive payments were available for buildings that participated in their new commercial building demand-side management program, Energy FinAnswer, described below.

The term "building commissioning" has its roots in ship building industry to describe the activity of testing the ship's technical systems. The term emerged within the building industry during the late 1980s. As Claridge et al. (1994) point out, one telling metric of its emergence in the building industry is the number of articles written on the subject over the last few years, which went from zero a few years ago, to dozens of citations.

Commissioning is not common practice, and it means different things to different people. There are several factors that have driven the development of commissioning as a stand-alone practice. These include increasing complexity of controls, interests in energy-efficiency and demand-side management, growing knowledge (from detailed metering projects) of the frequency of operating problems in buildings, and indoor air quality concerns.

In general, improvements in indoor air quality and other non-energy benefits may be more important than the energy saving benefits from commissioning. Ensuring proper air flow in a building influences the health, safety, and productivity of the occupants (Sterling and Collett, 1994). Energy costs in office buildings are around \$1/ft^2-year, while salaries of employees are about two orders of magnitude greater. The ultimate bottom line is the health and productivity of the occupants. Showing quantified occupant productivity gains in a well commissioned building compared to a building that is not commissioned is extremely difficult. However, we can show that the types of problems found during commissioning, left uncorrected, result in suboptimal building performance.

In order to evaluate the benefits of commissioning it is important to understand the broad range in the scope of commissioning as it is done today. There is no universal or even dominant approach utilized in this emerging activity. The American Society for Heating, Refrigeration, and Air-Conditioning Engineers is currently updating their commissioning guidelines (ASHRAE, 1989). These guidelines are probably the most widely utilized document on this subject in the U.S. The ASHRAE guidelines focus on HVAC commissioning, while many commissioning projects involve building systems beyond HVAC.

This study focuses on commissioning of individual EEMs. The performance of an EEM is often linked to other building systems. Many of the commissioning agents responsible for commissioning of the 16 buildings described in this study performed EEM commissioning with a broad eye for how the EEM integrated with other building systems. Others took a more narrow view, and might have missed broader control and system integration issues. As noted throughout the analysis, we found significant energy savings benefits from EEM commissioning that went beyond the savings of the individual EEM.

In light of the complex interactions of building systems, commissioning is particularly helpful in improving the performance of the connective systems within a building, such as thermal distribution systems or controls. These subsystems are often weak links in whole-building performance. Specific components, such as chillers, heat pumps, or motors, are currently subject to standardized performance tests to rate their energy performance with a metric such as a coefficient of performance (COP), or energy-efficiency ratio (EER). Such tests are defined by the American Refrigeration Institute, ASHRAE, and others. Installed building systems, however, are not usually subject to any standard acceptance tests. Commissioning tests are designed to help identify problems with both individual pieces of equipment and with their connection to other building systems. For example, the fans and pumps of a cooling tower fan should be on when needed to cool chiller condenser water. We found several examples of improper integration of the controls between cooling towers and chillers, such as the cooling tower pump running continuously and variable frequency drives on the cooling tower fans running at constant speed.

How can we encourage greater use of commissioning processes in common practice? This question is of great interest to energy planners and others. Case studies of the costs and benefits of commissioning were considered a top need for increasing awareness of commissioning (Benner and Bjornskov, 1994). There is not much information available on this topic. Only one other study has been published that discusses the costs and benefits of utility funded EEM commissioning. The scope of this study by Stum and Haasl (1994) was more limited, focusing on inspecting economizers and programmable thermostats. This study is unique in that we look at the cost-effectiveness of commissioning a broad range of EEMs.

This lack of information about the costs and benefits of commissioning is a clear gap in the information available to encourage further investments in commissioning. Although the results discussed below are based on a small sample (16) of buildings, the results are favorable, showing a need for further investment in this type of analysis in order to better understand how to optimize investments in commissioning. It is important for utilities and building owners to carefully track what was done during "commissioning," and attempt to quantify the benefits, or at least track the findings from commissioning.

Project Goals and Scope

The broad goal of this study is to improve understanding of the value of commissioning and its potential for enhancing commercial energy-efficiency programs and policies. We address this goal by analyzing the energy savings and economic benefits of commissioning in 16 buildings (labeled Building A though P). The costs for the energy-efficiency measures and for commissioning are compared against the monetary value of the predicted energy savings for each measure, and the savings from correcting deficiences found during commissioning. We explicitly address the question of how much of the predicted savings from the EEMs might have been lost without commissioning. The broader questions are, " are the EEMs still cost effective with the added cost of commissioning?" or perhaps "are they more cost effective with commissioning?" The costs for commissioning are also assessed with commissioning as a stand-alone measure.

The evaluation began with a pilot study on two of the 16 buildings to develop a methodology for quantifying the energy savings impacts and non-energy benefits from commissioning. Part of the pilot analysis was to develop standard terminology to describe how the corrected deficiences relate to the EEMs. As described below, PacifiCorp's commissioning program is designed to ensure that individual EEMs perform according to design intent. This activity is often considered "EEM" commissioning, as opposed to whole-building commissioning that is broader in scope. Despite the EEM orientation, we found many non-EEM or whole-building energy savings and other non-energy benefits from commissioning. This suggests that the distinction between EEM and whole-building is blurred by the integrated nature of building systems, especially in large buildings where the controls are more integrated.

It is difficult to quantify the savings impacts of commissioning because of uncertainties regarding the energy consuming characteristics of individual buildings. Also, commissioning practices differ from building to building just as the building systems themselves differ. Perhaps the most robust method to develop such estimates would be to compare a large number of closely monitored commercial buildings that are commissioned with a similar group that are not. Detailed monitoring of all sites, with careful tracking of building system characteristics and deficiency corrections would in theory reveal the energy impacts of commissioning. Such a study would be expensive and difficult to conduct.[1]

---

[1] For example, the Energy Edge research and demonstration project covering 28 new commercial buildings required $15,000,000 for seven years of design assistance, monitoring, and modeling. Models were used to develop common practice baseline buildings.

As a result of the uncertainties associated with quantifying the benefits from commissioning, the estimates in this study are generally conservative. The estimates are a defensible lower bound of the savings. The actual savings are probably larger than those we're able to quantify. In several cases we discuss savings from deficiency corrections that are higher than the savings we track in the economic analysis (e.g. see discussion of Buildings E and G). Another reason that the estimates are conservative is that we only quantified energy savings for deficiences that we knew were corrected. In many cases the commissioning agent listed deficiences that were not-corrected, or were outstanding at the time that they did their final inspections. It is likely that the building operations staff addressed many of these outstanding issues, but without hard evidence, we avoided claiming benefits from simply identifying a deficiency.

While we have focused on quantifying the energy savings benefits of commissioning, we have also tracked and categorized non-energy benefits that may prove to be as important, if not more important than the energy savings benefits. Examples of non-energy benefits are improved thermal comfort, improved indoor air quality, and lengthened equipment life. Specific examples of these and other non-energy benefits are presented below. A broad definition of the benefits may be more important to the building owner than to the utility, as the building owner has a broader interest in overall building performance. However, as utilities shift from energy providers to diversified service companies, programs that offer non-energy benefits to utility customers will likely become more important.

The focus of this study is on new buildings. There is one major renovation among the 16 buildings. Commissioning processes can also be applied to existing buildings, often referred to as "recommissioning." This term could be misleading because most buildings are not commissioned to begin with.

Report Organization

Following this introduction are six sections of the report. Section 2 discusses the Energy FinAnswer program and the procedures for commissioning. Section 3 presents the evaluation methodology, describing the derivation of the energy savings estimates, the economic analysis, and the definitions of non-energy benefits tracked, but not included in the economic analysis. Section 4 describes energy savings of commissioning for each building. Section 5 compares the energy savings and cost-effectiveness of commissioning among all 16 buildings. Section 6 discusses the implications of the results, key uncertainties, and future directions. Section 7 provides references. An unpublished appendix is available from LBL that contains additional details on the assumptions and estimation methods for each building.

2. Commissioning within Energy FinAnswer

The commissioning activities sponsored by PacifiCorp are offered as part of the Energy FinAnswer demand-side management program. Energy FinAnswer includes financial and engineering services for energy-efficiency measures. Commissioning services are available for new commercial buildings larger than 12,000 ft^2 and for major renovations.

The Energy FinAnswer program is based on economic analysis of energy savings estimate modeled for each EEM. The estimates were developed with DOE-2 simulations, performed parametrically against a baseline simulation. An interactive model is also run with all of the static and dynamic EEMs included, defined in the following paragraph. Dynamic EEMs are those involving controls and heating, ventilating, and air-conditioning (HVAC) systems; these are checked during commissioning. Static EEMs, by contrast, are those that stay in place and do not receive control signals, low-e windows or wall insulation.[2] Lighting systems have both static and dynamic components. Lighting controls, such as sweeps and daylighting systems were considered dynamic systems. Occupancy sensors were generally considered by PacifiCorp as static systems. Several of the commissioning agents examined their performance because they are dynamic, or active, in nature, and therefore are subject to potential control and operations errors.

Energy FinAnswer provides loans to the building owner for the incremental cost of the EEMs. The package of measures must reduce energy use by at least ten percent beyond the simulated code baseline. The utility recovers the investment through a service charge on the utility bill. The customer benefits from the reduced monthly bill, which, in theory, is reduced by more than the service charge. The design analysis for each building is summarized in the Final Modeling Report. These summaries describe the DOE-2 simulations for each EEM, and PacifiCorp's financial evaluation[3].

Commissioning of each building project begins with the selection of a Commissioning Agent (CA). The CA's primary responsibility is to ensure that all of the funded dynamic EEMs are installed and operating according to the design intent. CAs sometimes assist in training building personnel in proper equipment operations and maintenance (O&M). The commissioning procedure consists of the following elements:

- *Scoping Meeting —*
  The CA meets with the building designers, contractors, and the utility's Technical Coordinator to discuss the commissioning process.
- *Commissioning Outline —*
  The CA outlines a commissioning schedule, construction contractor responsibilities, outstanding information requirements, equipment and system test procedures, monitoring plan (if any), and building operator training.

---

[2] Within Energy FinAnswer, static EEMs are verified as installed and operational through visual inspections that are separate from commissioning.

[3] PacifiCorp's service territory includes parts of Oregon, Utah, California, Montana, Wyoming, Washington, and Idaho. The baseline assumptions by region are slightly different because of differences in the state energy codes. That is, an EEM may save more energy if the baseline is the Utah code compared to EEM savings calculated from the more stringent Oregon code.

- *Pre-Commissioning Tests —*
  These tests are designed by the CA and conducted by the contractors to verify that the equipment and controls are actually operating.
- *Functional Performance Tests —*
  Often seen as the heart of commissioning, these tests are designed to review if the design is adequate, the controls are properly calibrated and appropriate, the control sequences are correct, and the proper actions occur in response to defined stimuli.
- *Operations and Maintenance Summary and Training —*
  The CA reviews the training procedures and O&M manuals to ensure that proper attention is given to the O&M characteristics of the EEMs.
- *Documentation and Final Commissioning Report —*
  CAs submit a variety of progress reports to the Technical Coordinator. The final report contains the building description, commissioning issues, field work, pre-commissioning verification and functional performance test results.

The most common arrangement in non-utility funded commissioning is for the CA, whether an independent contractor or part of the mechanical and electrical team, to work directly for the building owner. In this program, however, the CA is under contract with the utility to provide the commissioning services. That is, the utility pays for the commissioning. The contractors are normally responsible for correcting deficiences identified by the CA. Usually the CA tracks the activities required to correct deficiences. Nearly every building, however, has some outstanding deficiences, which are usually minor in nature.

As mentioned, the PacifiCorp program continues to evolve. Recent changes involve developing standardized specifications for EEMs and related commissioning activities. These procedures will be developed from the documentation on commissioning tests performed over the last few years. The utility may also change the contractual agreements by requiring the building owner to contract directly with the CA.

3. Evaluation Methodology

This section discusses the procedures used to quantify the energy and associated dollar savings from commissioning. We also discuss non-energy benefits. The evaluation methodology was designed to make maximum use of the building documentation developed by PacifiCorp as part of their program. Two buildings were selected for a pilot analysis conducted to refine the evaluation methodology.

In the pilot analysis we explored several issues that were beyond the scope of the analysis for all 16 buildings. These issues included examining the method used to detect the deficiency (e.g., trend logs, spot metering, observation), actions taken to correct the problem (e.g., call to contractor or manufacturer) and results of the action (repaired or not). This information could be useful, however, in considering the likelihood that a problem would have gone undetected without commissioning. This analysis would also have required more details than those typically available in the Commissioning Reports. We did, however, carefully track the last item for all of the buildings: the result of the action.

This study explores the benefits of deficiences we know were corrected. The evaluation consisted of the following steps:

- Select case study buildings
- Compile general building information
- List corrected deficiences by building
- Quantify energy savings
- Conduct cost-effectiveness analysis
- Characterize non-energy benefits by building
- Compare results among buildings

The following section describes these steps in further detail.

Building Selection and Documentation

LBL worked with PacifiCorp and the Technical Coordinator to develop the evaluation methodology and select the buildings for case study analysis. Ten attributes of the commissioning projects were defined by LBL and the Technical Coordinator. The Technical Coordinator developed a weighting system so that certain attributes were given a higher value in the selection process. Information on approximately 50 buildings was available to choose from. The ten attributes were:

- Quality of final commissioning report
- Quality of DOE-2 design model
- CA capabilities
- Representativeness of commissioning deficiences
- Availability of information about equipment
- Availability of commissioning cost data by EEM
- Availability of subsystem metered data from the CA
- Availability of hourly whole-building data by PacifiCorp

- Building type (office, retail, etc.)
- Completeness of commissioning

The items near the top of the list were more important than those near the bottom. The intent was to select buildings with good documentation of the commissioning process. The buildings selected are considered to be fairly typical of those found in the program at large.

After the 16 buildings were selected, we compiled general building characteristics data for each building. This information consisted of the following:

- *Building Characteristics -*
  name, size, location, energy use.

  Sources: Final Modeling Reports, DOE-2 Building Description Language, and Final Commissioning Report
- *Energy-Efficiency Measures -*
  description of measures (static and dynamic), energy savings by type (gas, electric, etc.), measure cost, energy cost savings, parametric and interactive savings (from DOE-2).

  Sources: Final Modeling Reports, DOE-2 Building Description Language, and Final Commissioning Report
- *Commissioning Activities-*
  CA's name, address, project status.

  Sources: Final Commissioning Report, Technical Coordinator's notes and "War Story" list. We also examined observation reports, non-compliance reports, and CA status reports.

Corrected Deficiences

The information described in the previous section was recorded in a UNIX based database. The number of corrected deficiences at each building ranged from zero to 13. Developing the list was no simple task because commissioning agents are busy field analysts, and not always proficient at documenting their activities and describing deficiences identified during functional and diagnostic testing. The utility's Technical Coordinator informally developed a humorously named "War Story" list of one-line descriptions of deficiences found at most sites. The descriptions on this list were carefully checked against the lists developed from the final commissioning reports, which differed slightly.

In many cases it was unclear if a deficiency was corrected or not. The construction contractors, such as the mechanical, electrical, and controls contractors, were responsible for making the corrections. In most cases the final commissioning report included a discussion of the deficiences found during commissioning, which sometimes included notes on when they were corrected. There were often outstanding deficiences left uncorrected. The aim of commissioning was to identify the most important operational problems, and our primary concern was to characterize the energy saving benefits of the most important deficiencies that were corrected. The fact that there are outstanding deficiences highlights the fact that the **technical** potential for energy savings from commissioning is greater than the savings captured by the current scope of activities. The **economic** potential, however, is not easy to assess. There are diminishing returns for a CA to follow up on small details that don't make a large impact on energy or other operating costs. Defining the appropriate level of intervention and associated funding for commissioning is difficult, but a topic of great interest to PacifiCorp and other utilities.

In defining a deficiency, we generally assumed that a commissioning action or intervention addressed a problem that would have gone uncorrected without commissioning. This may be incorrect in some cases. A building operator could identify and correct an operating problem, such as a non-varying variable frequency drive (VFD) within the first year of building occupancy. Some of the uncertainty as to whether a deficiency would have been corrected is incorporated in the economic analysis. As described below, two correction lifetimes, a low and high value were assumed.

An important part of the methodology was to evaluate how the deficiences related to the energy savings estimates for the EEMs. We have defined three categories of relationships: directly related to the EEM, indirectly related to the EEM, and unrelated to or beyond the EEM. These definitions are as follows:

- *Directly Related to EEM* —

  These deficiences are directly related to the EEM. For example, correcting a VFD control problem that prevented the motor from varying addresses a problem with the energy saving characteristics of the EEM. Correcting a deficiency directly related to an EEM results in energy savings that are some fraction of the savings from EEM itself. **Once an EEM is commissioned we assume that the savings are 100 percent of the predicted savings.** This is a simplification in the analysis methodology because we did not have the resources to conduct detailed monitoring for EEM verification.

- *Indirectly Related to EEM* —

  There are two types of indirect savings. First are deficiences indirectly related to the EEM because **they also would have been found in a baseline system without the EEM.** For example, the EEM funds may cover the purchase of a heat pump with a COP beyond the code baseline COP. In several buildings construction debris dirtied filters, which decreases heat pump efficiencies because air flow rates are reduced and heat pump coil temperatures rise. This reduction in efficiency would have also been present in the baseline heat pump system.

  Second, a commissioning agent may fine-tune an EEM, going beyond the basic design intent, which is sometimes referred to as "super commissioning." For example, one of the CAs optimized the heat recovery system control, thereby reducing the occurrence of simultaneous heating and cooling. The energy savings from this improvement was not included in the original design study.

- *Unrelated to EEM* —

  These deficiences are not related to the EEMs at all, and could have been found in a baseline building that did not have the EEMs. For example, one building had a problem in the wiring of the resistance heat that did not directly involve the EEMs. The wiring problem had nothing to do with the fact that the heat pump had a higher COP than the baseline system.

Figure 3.1 illustrates how the energy savings from the EEMs relate to the energy savings from deficiency corrections. The total energy savings from the financing of the dynamic EEMs and the commissioning combined is the savings from EEMs plus the savings from the indirect and unrelated corrected deficiences.

Quantifying Energy Savings

After developing the list of deficiency corrections, we examined information available about the building and the description of the corrected deficiences to determine which corrections would be subject to further analysis to estimate their energy savings benefit. Deficiences that were corrected but that appeared unreasonable to quantify energy savings benefits were assigned one or more non-energy benefits, as further described below. For example, there were several examples of missing thermostats being added or thermostats recalibrated. These improvements clearly improve the ability to control space temperatures, but the net effect on energy use is unclear. Energy use could increase or decrease depending on how the zone related to other zones and the overall control scheme.

The techniques used to estimate the energy savings from commissioning fall into the following five categories:

- *Prediction* —
  Direct use of the design-phase predicted savings. This is appropriate if the EEM was completely defeated without commissioning.
- *Engineering Estimate* —
  Hand calculation based on engineering principles.
- *Monitored* —
  Extrapolated from short-term monitored data to annual savings.
- *DOE-2 Simulation* —
  Simulation based on changes to design model.
- *Combined Approach* —
  Combined DOE-2 simulation from design model with hand calculations.

By far the most common method used in this study was the DOE-2 simulation approach. Before discussing this approach we review differences among the others.

Direct use of the design-phase predicted savings is applicable for deficiency corrections in which the EEM would have been completely defeated without commissioning. For example, the daylighting dimming EEM malfunctioned at Building G. The dimming system was defeated until the manufacturer added a cone to modify the sensor's field of view. The savings from commissioning are equivalent to the predicted energy savings.[4]

Engineering estimates were developed outside of DOE-2 when DOE-2 was inappropriate or unavailable for use. For example, we used engineering principles to estimate energy savings from correcting the control wiring of the control of resistance heat at Building B. This could not be modeled directly because of limitations of the modeling procedures within DOE-2. In a few cases key assumptions in the engineering estimates were based on monitored data, adding greater certainty to the estimate. In such cases we extrapolated from short-term measurements to annual savings.

---

[4] This is the only occurrence of this quantification method in the study, which may slightly overestimate savings because of measure interactions.

Modeling of the energy savings from correcting a deficiency is the difference between the final interactive model (with all of the EEMs working) and the model we develop changed to represent the improper system. A significant benefit of using DOE-2 as the foundation for energy savings estimates is that it captures the interactions that occur between complex building systems, such as thermal interactions between lights and HVAC systems. Another advantage of DOE-2 is that the savings estimates are easily replicated, easily archived and documented, and referenced to a specific set of simulation files.

Again, this study is not one oriented toward verifying how the measures worked in the field. Rather, our objective is to quantify energy saving benefits of commissioning. We assume that the design predictions are reasonable estimates of the savings for each measure. One shortcoming of this approach is the fact that actual buildings and installed system characteristics often differ, sometimes dramatically, from assumptions used in design models. These differences complicate the use of DOE-2 in evaluating energy savings from commissioning. We have not made extensive changes to the design models to reflect information about the actual building or used monitored data to calibrate the models. The information needed to conduct such model tuning was beyond the scope of this study.

Section 6 discusses some of the key uncertainties and difficulties with using the original design studies as the baseline conditions for judging commissioning savings. Problems with both the simulation input files and the design reports are discussed. These problems could have been minimized with higher standards of quality control and design review.

Three types of energy savings benefits were tracked: electricity (kWh), natural gas (kBtu), and peak electric demand (kW). All of the electricity savings are in site energy units. The estimates of demand savings from deficiency corrections are estimates of the average monthly peak demand shift. Some demand shifts occur only during the heating or cooling seasons. In such a case we estimated that the shift would have occurred for only 6 months of the year, but still averaged the peak shift over the entire year. For example, a chiller COP improvement that saved 1 kW/month for six months is equivalent to shifting 0.5 kW each month for the entire year. (As described below, the demand savings were treated in this manner because the peak demand cost savings were estimated to be $5.5/kW per month, for all 12 months.)

Comparison of Commissioning Savings to EEM Savings

The primary motivation for PacifiCorp to fund commissioning is that some unknown fraction of the predicted energy savings from each dynamic EEM would be lost without it. One objective of this study was to estimate this fraction. This estimate is done two ways. One method compares the total savings from commissioning, including direct, indirect and unrelated savings, to the predicted EEM savings. The second method compares only the direct savings from commissioning with the predicted EEM savings. We examine this information in both forms because one might have thought that all of the savings were direct savings. Many of the deficiences found during commissioning would have been found whether or not the EEM was installed.

The EEM savings estimates within Energy FinAnswer are based on parametric simulation runs against the baseline building that meets the local building code. Parametric savings estimates are often greater than interactive savings estimates. For example, the savings from a simulation of a baseline and energy-efficient heat pump will be greater for a heating dominated building without the extra roof insulation that might be included in a package of measures. When the insulation is increased, the savings in improving the heating system efficiency is lowered.

On average, for these 16 buildings, the total interactive savings was nearly identical to the parametric savings (further discussed below, and shown in Table 5.3). This average was dominated by an anomalous building where the difference between parametric and interactive savings was greater than a factor of two. The interactive savings were less than the parametric savings for 13 of the 16 buildings, and the median difference between the parametric and interactive savings was 7 percent. That is, the interactive savings were typically 7 percent less than the parametric savings. This is further discussed in Section 5.

We compare the energy savings estimates from the deficiences with the predicted savings for the EEMs at two levels: for the whole building, and for individual EEMs. Only the whole-building comparisons were corrected for differences between the interactive and parametric. The energy savings estimates for the deficiences are based on parametric simulations against the interactive run. Therefore, the ratio of the direct energy savings from commissioning to the EEM is lower than if the commissioning savings were estimated against the baseline. In comparing commissioning savings with EEM savings we adjust the commissioning savings based on the ratio of the interactive to the parametric savings, as discussed below. This is done for the electric savings only.

Non-Energy and Non-Quantified Benefits

The primary motivations for commissioning within Energy FinAnswer is to capture energy savings by ensuring that building systems work as intended. There are also many non-energy benefits accrue as a result of commissioning. In many cases these non-energy benefits may be more significant than the energy savings benefits. Properly commissioned office buildings are likely to be more comfortable, thereby providing environments for increased occupant productivity. The salaries of building occupants are much greater than any other costs, such as rent, or energy costs. Any gain in productivity could far outweigh the value of energy savings. Even a small increase in worker productivity would quickly pay for the costs associated with commissioning.

It is extremely difficult, however, to measure comfort and productivity gains. Quantifying comfort improvements and other non-energy benefits is more difficult than quantifying energy savings benefits. We assigned one or more non-energy benefits to each deficiency correction for which there were no energy savings benefits developed. Many of the corrections for which there were energy savings also had non-energy benefits assigned. This categorization scheme expands upon one developed for PacifiCorp by Kaplan (1993). The non-energy benefit categories are described below.

- *Improved Indoor Environmental Quality and Comfort (IEQ)* —
  This broad category is concerned with the quality of the indoor environment. As mentioned, deficiences corrections that improve the indoor environment can greatly enhance the comfort and productivity of building occupants. For example, improved air flow helps ensure that minimum ventilation requirements are met or exceeded. Improved temperature control helps ensure that the zone thermal conditions are adequate. One commissioning agent found a shipping block that was not removed from a new compressor. Removing it reduced a significant amount of vibration and noise, and improved occupant comfort.

- *Improved Controls and Zoning (CON)* —
  Similar to improved environmental comfort, this non-energy benefit is oriented toward the robustness of the building control system itself. Correcting malfunctions and optimizing operations of building controls is one of the primary benefits of commissioning, as discussed below.
- *Reduce Operations and Maintenance Costs (O&M)* —
  Many corrected building deficiences improve overall operations and maintenance beyond the controls and zoning described in the pervious paragraph. This is a general benefit. Commissioning should help ensure that O&M problems found during start-up will be less likely to occur during ongoing O&M.
- *Improved Equipment Life (EQT)* —
  Commissioning helps to correct system deficiences that may reduce useful equipment life. Increasing equipment life is related to improvements in O&M since proper servicing can greatly reduce the wear and tear on many systems. In fact, the benefits from correcting the operating conditions of some equipment may far outweigh the energy savings benefits when deficiences are corrected that might have lead to serious equipment failures. As discussed below, there were several instances where equipment cycled too frequently, placing undue stress on motors and other components, which may have lead to premature and extreme failures.
- *Reduced EEM Dollars* —
  Part of the commissioning was to verify that the installed system was consistent with the design specifications. Financing was reduced or dropped if there were significant differences. There were several changes in the EEM funding of both static and dynamic measures among the 16 buildings. The CA was responsible only for the dynamic EEMs.

There were several miscellaneous benefits that were outside the scope of the above categories. For example, there was a change in the temperature of a grocery freezer that will improve the quality of the frozen food. Another benefit of commissioning is the reduction in contractor call-backs or change orders. This benefit can reduce construction costs. We were unable to explicitly track this latter non-energy benefit because of a lack of information on whether the deficiency would have warranted a call-back or change order. It is quite likely, however, that this was an important benefit in many circumstances.

Our intention in this study was to only assign energy savings benefits to deficiency corrections where we had some reasonable confidence that the savings were tangible. That is, in a few cases we did not quantify the energy savings from deficiency corrections that were likely to have saved energy, but were extremely difficult to quantify. We tracked several of these as non-quantified additional energy savings.

Cost Effectiveness

The economic analysis was designed to address the broad question: **was commissioning cost effective?** To address this question we examined the cost effectiveness three ways. First, we looked at the economic performance of the dynamic EEMs without commissioning. Second, we looked at the cost-effectiveness of commissioning as a stand-alone measure. Third, we looked at the cost-effectiveness of commissioning when combined with predicted costs and savings of the EEMs.

In the first case of looking at the economic performance of the EEMs without commissioning we calculated the simple payback times of the EEMs. This analysis involved examining the energy savings and economic data we received directly from PacifiCorp.

The second case of looking at the cost-effectiveness of commissioning as a stand-alone measure is probably the most important of the three, and is also straightforward. Here we compare the total energy cost savings from commissioning with the total costs paid by Energy FinAnswer for commissioning. The total cost savings include direct, indirect, and unrelated savings.

In the third case of looking at the cost-effectiveness of the EEMs and commissioning combined we account for direct, indirect, and unrelated savings differently. Here we assume that once commissioned, the EEM saves 100 percent of the design predicted energy savings. But, in addition to those savings, there are additional indirect and unrelated savings from commissioning. So, here we compare the costs for commissioning plus the EEMs with the savings from the EEMs plus indirect and unrelated energy savings.

As mentioned earlier, in general the economic analysis is conservative. That is, we have not been aggressive in quantifying the economic benefit of every possible positive attribute of commissioning that can be defined for each building. Rather, we have sought to establish the energy savings and related economic benefit of the most important and well understood deficiency corrections.

Predicted energy savings estimates are available for each measure. Similarly, the energy savings from commissioning are estimated for each deficiency correction. The economic analysis was conducted on a whole-building basis. This is because commissioning costs were not generally available by EEM. The data available consisted of total costs for commissioning the package of measures for each building.

Two series of economic parameters were developed. First, as mentioned, we estimated simple payback times for the dynamic EEMs funded by Energy FinAnswer, for the commissioning as a stand-alone measure, and for the EEMs and commissioning combined. The payback time is the ratio of first costs (for EEMs or commissioning) to the annual energy savings. Second, a series of present value (PV) savings estimates were developed. The PV considers the number of years that the energy savings are present and the time-value of money. By definition, the PV is the annual savings divided by the appropriate capital recovery factor, or:

$$PV = \frac{\text{annual energy savings}(\$/yr) \times (1 - (1 + d)^{-n})}{d}$$

where d is the real annual discount rate (3.5 percent, which is equivalent to the cost of capital at 8.5 percent less inflation at 5 percent) and n is the EEM or commissioning deficiency correction lifetime in years. The present value of the energy savings from an EEM or from commissioning can be compared to the initial investments to estimate the net present value of an investment, or a cost-benefit ratio.

To estimate the PV for the case where the EEMs and commissioning is combined we first derive the PV separately for each EEM and deficiency correction. We then sum the PVs to estimate the PV for the entire building.

Three different components of energy costs were tracked: electricity (kWh), natural gas (kBtu), and electric peak demand (kW). The energy cost savings include all three components of energy costs whenever applicable. All electricity data are in site units. Energy prices vary greatly among the buildings. To simplify the comparison of the economic parameters we choose to use a consistent set of energy prices for all 16 buildings: 4.0 ¢/kWh for electricity, $4.5/MBtu for gas. The peak demand costs were estimated to be $5.5/kW per month, for all 12 months. These energy costs are midrange values representative of average costs for PacifiCorp.

There is significant uncertainty in the lifetime of a deficiency correction. To help account for this uncertainty we estimated a high and a low correction lifetime. About 80 percent of the 36 quantified deficiency corrections had 5 years as the low lifetime estimate and 15 years as the high lifetime estimate. One to two-year lifetimes were assumed for the economizer corrections because of they are notorious for having problems (Piette et al, 1994; Kaplan, 1994). The high correction lifetime assumes that the deficiency correction remains effective for the life of the measure as defined within the design study. The low lifetime represents the conditions under which the deficiency may not remain corrected. Changes in building conditions, controls, schedules, or equipment degradation could defeat the savings from the correction. Another factor is that the deficiences may have been corrected by a building operator at some future time, therefore the lifetime of the savings from commissioning is less.

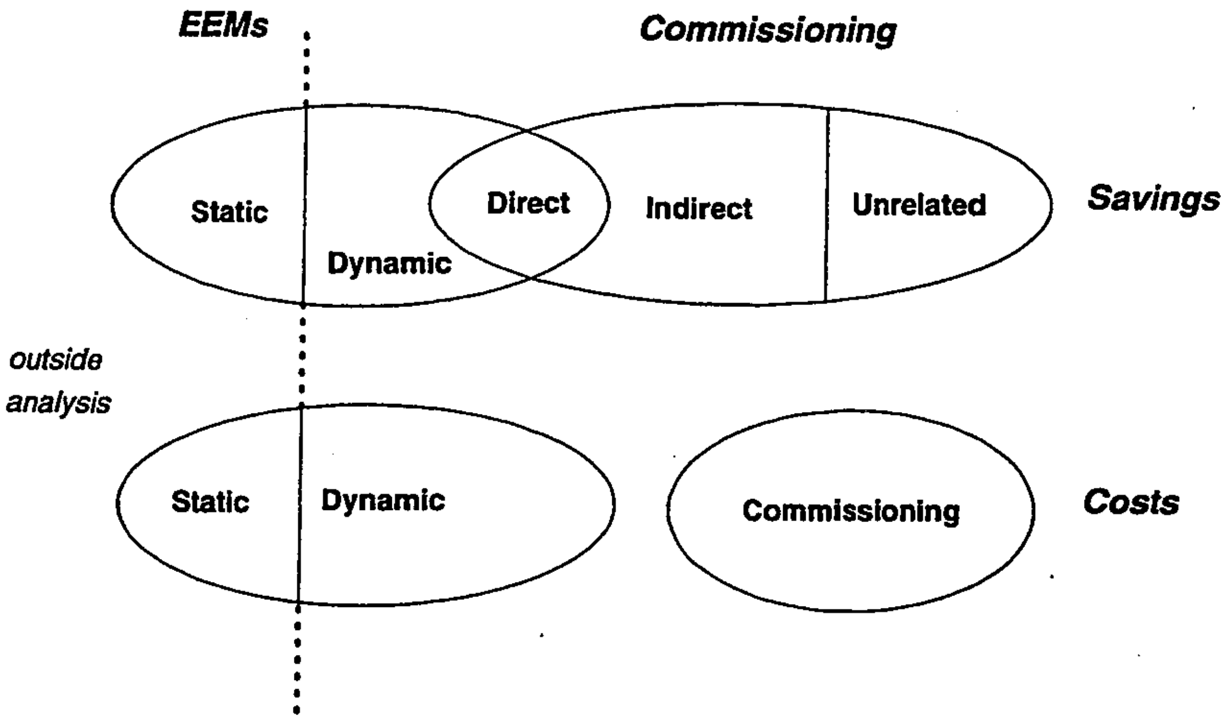

Figure 3.1. Relationship between costs and savings from the EEMs and commissioning. Only dynamic EEMs, such as controls and HVAC system, were commissioned. Energy savings from repairing deficiences found during commissioning can be categorized as those that directly relate to the EEM, those that indirectly relate to the EEM, and those that are unrelated to the EEM.

4. Results By Building

Overview of Buildings and EEM Savings

Sixteen buildings have been analyzed according to the case study methodology described in the previous section. These buildings are listed in Table 4.1. Most of the buildings are in Oregon, several are in Utah, and one in California. Half of the buildings are offices and the others are a mixture, with retail, lodging, grocery, hospital, warehouse, and theater buildings. The buildings range in size from 12,500 ft^2, to 312,000 ft^2.

Table 4.1 Description of Buildings and Efficiency Investments.

Code	Type	Floor Area *(kft^2)*	Total Efficiency Investment Total *($/ft^2)*	Static *(%)*	Dynamic *(%)*	Cx[c] *(%)*	EEM Savings[a] Elec. *(kWh/ft^2-yr)*	Dollars *($/ft^2-yr)*	Percent Dynamic[b]
A	Office	19.8	3.36	27	71	2	3.91	0.36	75
B	Office	21.8	2.44	60	26	14	6.00	0.35	21
C	Office	24.8	0.74	74	4	22	2.04	0.71	80
D	Office	34.0	4.17	53	36	11	6.80	0.61	50
E	Office	66.0	2.98	41	57	3	8.20	0.49	28
F	Office	66.4	4.02	46	52	2	18.41	0.85	23
G	Office	84.1	3.15	54	41	6	13.44	0.71	68
H	Office	312.0	6.95	48	51	1	15.63	0.94	59
I	Theater	12.5	1.60	58	29	13	4.38	0.22	12
J	Retail	17.0	1.33	78	13	9	5.06	0.22	11
K	Retail	17.0	4.85	82	10	8	4.32	0.27	11
L	Grocery	19.4	17.06	7	91	2	34.39	1.60	79
M	Hospital	23.0	3.17	73	21	6	7.00	0.43	18
N	Motel	29.0	1.98	23	45	32	2.10	0.15	61
O	Grocery	38.5	4.28	19	76	4	12.54	1.86	79
P	Hotel	64.5	10.60	75	23	2	7.47	0.41	31
Average		53.1	4.54	51	40	8	9.48	0.64	44

[a] These are based on the interactive savings, not the sum of the parametric savings.
[b] This is the dynamic percent of the total annual dollar parametric savings.
[c] Commissioning

Table 4.1 shows the variation in the efficiency investment at each site. The total investment, consisting of the loan from PacifiCorp for the EEMs and direct payment by PacifiCorp for commissioning, ranged from \$1.6/ft^2 to \$17.1/ft^2. These costs are based on the original cost estimates prior to installation verification and commissioning. There were minor changes in the final payments for several of the buildings, primarily reductions in the static costs. Changes in installed dynamic measures identified during commissioning resulted in reductions in the dynamic measure costs at two buildings (N and O).

The costs for commissioning varied from 2 percent to 32 percent of the total investment, with an average of 8%. The distribution of commissioning costs for the 16 case study buildings is similar to the distribution for the larger set of buildings that PacifiCorp provided data on. As shown in Figure 4.1, the costs for commissioning in the case study buildings ranged from \$0.07/ft^2 to \$0.64 \$/ft^2. The average commissioning of \$0.23 ft^2 is identical to the average for the larger population of 50 buildings commissioned within Energy FinAnswer (Yoder, 1994). The purpose of Figure 4.1 is to show that the costs for commissioning in these 16 buildings is similar to the larger sample. The predicted dynamic EEM energy savings for these 16 buildings are similar to the large population. The figure shows the commissioning costs versus predicted EEM savings for the dynamic measures. The EEMs were predicted to save between 2.1 kWh/ft^2-yr (Office B) and 34.4 kWh/ft^2-yr (Grocery K), as shown in Table 4.1.

Energy Savings by Building

In this section we discuss the dynamic EEMs and the energy savings from commissioning for each building. Energy savings for 36 deficiency corrections are described. Following a brief discussion of the energy savings from commissioning is is a table that lists the predicted energy savings for each dynamic EEMs and the total energy savings for all dynamic EEMs. As discussed in Chapter 3, these EEM savings are parametric estimates. The second part of the table lists the deficiences corrected during commissioning and the energy savings estimates for the correction. Corrections are categorized as direct, indirect, and unrelated. Unlike the EEM energy savings estimates, the energy savings estimates for commissioning are based on the interactive model. Direct and indirect savings are listed below the EEM name, which is repeated from the first part of the table. Indirect savings are shown in italics. The table also shows the energy savings from direct corrections as a percentage of the predicted savings for the related EEM and for the total of the dynamic EEMs. Additional details on the description of the commissioning problem and assumptions used to estimate the energy savings are provided in an appendix

Office Building A

The EEMs in this office building consisted of a ground-coupled water-source heat pump and lighting improvements. The lighting EEM includes T-8 lamps, electronic ballasts, and occupancy sensors with built-in photocells. The daylight dimming photocells were not adjusted by the installation contractor. The CA developed and executed a procedure for testing and adjusting the daylighting system. He corrected about half of the controllers that were not functional, which had minimal energy savings. There were also several adjustments made to the ground-coupled water-source heat pump system. A missing thermostat was added, the loop temperature was adjusted, and the schedule and integration with the computer room controls were adjusted. As an example of the problems in comparing design and actual operations, the heat pump was originally designed to operate only during business hours but the inclusion of a 24-hour computer room in the loop forced 24-hour heat pump loop operation.

Table 4.2 lists the energy savings for the dynamic EEMs. There are no indirect or unrelated deficiency corrections for Building A; the one quantified deficiency correction is directly related to the EEM, accounting for 3 percent of the predicted energy savings. The energy savings from daylighting were only a small fraction of the energy savings in the entire lighting EEM.

Table 4.2 EEM and Energy Commissioning Savings for Building A.

	Electric		Gas		Demand	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Eff. Lights, Occ. Sensors, & Photocells	1.56				0.56	
Ground-Water Heat Pump	1.32				2.17	
Total—Dynamic EEMs	2.88				2.73	
Savings From Direct & *Indirect* Corrections						
Eff. Lights, Occ. Sensors, & Photocells Daylight Dimming Adjusted	0.04	3			0.02	3
Total—Direct Corrections	0.04	1			0.02	1
Total—All Corrections	0.04				0.02	

Office Building B

The problems at this office building were all HVAC related, as were the EEMs. Table 4.3 lists the three deficiency corrections. The first correction involved improving the heat pump efficiency by cleaning filters that were dirtied by construction debris and improving the refrigeration charge. In estimating the energy savings we assumed that the dirty filters and poor refrigerant charge would have degraded the COP by 15 percent. The dirty filters influence the COP because the air flow is reduced and the temperature differential across the coils increases. If the air flow is greatly reduced the coils can freeze, which occurred at this building.

The second correction involved a problem with the heating sequence. The CA found that the resistance heat was on whenever the heating was on. The controls were rewired so that the first stage of heating was compressor heat alone.

The third correction improved the economizers. The economizers on half of the ten rooftop systems were defeated because of problems such as poor linkages or blocked ducts. Two outdoor air ducts were blocked by plastic membranes leftover from construction. Another duct was blocked by a closed fire door. The energy savings shown in the table are less than half of the design prediction because we used the interactive model rather than the baseline with no EEMs.

Overall, 17 percent of the energy savings would not have been present without commissioning. Additional indirect energy savings of 0.8 kWh/ft^2-yr were obtained from addressing the heat pump problems.

Table 4.3. EEM and Commissioning Savings for Building B.

	Electric *kWh/ft^{2}yr*	 *% of EEM*	Gas *kBtu/ft^{2}yr*	 *% of EEM*	Demand *W/ft^{2}mth*	 *% of EEM*
Predicted Savings From Dynamic EEMs						
Efficient Heat Pumps	0.87				0.18	
Economizer Cycles	0.87					
Total—Dynamic EEMs	1.74				0.18	
Savings From Direct & *Indirect* Corrections						
Efficient Heat Pumps						
Filters Changed; Refrigerant Charged	*0.36*					
Resistance Heat Reduced	*0.43*				*0.57*	
Economizer Cycles						
Economizer Dampers Repaired	0.30	35				
Total—Direct Corrections	0.30	17				
Total—*Indirect Corrections*	*0.79*				*0.57*	
Total—All Corrections	1.09				0.57	

Office Building C

This building contains office and laboratory space. The sole dynamic EEM was a heat recovery wheel to preheat incoming outdoor air with exhaust air (Table 4.4). This strategy is particularly useful in buildings with large outdoor air requirements, such as laboratories, and is primarily heating, or gas saving measure. The CA made three improvements. First, he optimized the heat recovery efficiency by changing the rotational speed to obtain a measured improvement in the efficiency (36 percent to 70 percent). Second, he improved the DDC control strategy to reduce the likelihood of coincident heating and cooling. Third, he aligned one of the two wheels that was out of alignment, thereby increasing its useful life and reducing the wear and tear of the brushes that help keep air from leaking. This latter correction is discussed in the section below on non-energy benefits.

We modeled the energy savings from the improved efficiency within DOE-2, but encountered difficulties because of inconsistencies in the baseline model, which apparently had errors. The very high gas savings for the heat recovery EEM from the Energy FinAnswer tables appears to be an error. The gas savings from our estimate of the benefit from correcting the deficiency is based on working with what we believe is the correct DOE-2 model that is consistent with the majority of the design analysis simulation runs.

The energy savings from the DDC improvements go beyond the design intent estimate. This is an example of indirect EEM savings that might be thought of as "super commissioning." The savings estimate was based on assuming that the simultaneous heating and cooling would have occurred for about 40 hours per year.

Table 4.4. EEM and Commissioning Energy Savings for Building C.

	Electric		Gas		Demand	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Heat Recovery	0.07		121.93		0.20	
Total—Dynamic EEMs	0.07		121.93		0.20	
Savings From Direct & *Indirect* Corrections						
Heat Recovery						
Heat Wheel Efficiency Improved	0.04	54	1.42	1		
Heat Wheel DDC Control Improved	*0.18*					
Total—Direct Corrections	0.04	54	1.42	1		
Total—*Indirect Corrections*	*0.18*					
Total—All Corrections	0.22		1.42			

Office Building D

Building D was one of the two buildings in the pilot analysis. The commissioning corrected the control settings for the variable frequency drives on the relief fan and cooling tower, and corrected control of two variable-air-volume boxes (Table 4.5).

The relief fan variable frequency drive (VFD) was found to be inoperable because of a tripped protection device. We assumed that without the VFD the fan would have run at full speed during all operating hours (at 25,000 cfm, cubic-feet per minute) instead of full speed only during economizer hours, and minimum speed at other times (5,000 cfm). The commissioning agent's spot measurements of the building pressure setpoint were checked against assumptions for minimum flow conditions. The savings are derived from multiplying the power at minimum flow (1.7 kW) with the number of occupied hours not on economizer operation (roughly 2600, based on binned weather data).

Energy savings from the cooling tower VFD accrue when the fan speed is reduced because full air flow through the tower is not needed. The control problem defeated the energy savings from the VFD. We assumed that without proper VFD operation the fan would run at full speed for all occupied hours with outside air temperatures over 60°F, instead of the intended minimum speed at 60°F and maximum speed at 80°F. Interestingly, the DOE-2 design study concluded the savings for the cooling tower VFD were 22,000 kWh, seven times greater than our estimate. The DOE-2 design estimates included a cooling tower that was significantly larger than the actual cooling tower. Our estimates of the energy savings from commissioning is only 9% of the predicted savings. The commissioning agent noted that the installed cooling tower is actually undersized, which could result in comfort problems.

There were two problems with variable-air-volume (VAV) boxes: one box had a non-functioning heating valve and a second provided full cooling regardless of zone temperature. We assumed that the non-functioning heating valve was stuck fully open so that the controls would attempt to cool the zone since it would often be overheated. Using an average box at 1500 cfm we assumed that heating and cooling fight each other with no net effect at outside air temperatures above 60°F. To derive the energy savings we assumed a boiler efficiency of 80 percent, a chiller plant energy-efficiency ratio of 10 BTU/Wh, and 1200 hours/year of operation at outside temperatures above 60°F. The derivation of savings for the box stuck in cooling is similar. We assumed that while outside air temperatures are below 50°F the cooling is wasted and must be made up by heat from the adjacent zones. Furthermore, between 50°F and 80 °F the boiler and chiller fight, decreasing from full heating to no heating.

Table 4.5. EEM and Commissioning Energy Savings for Building D.

	Electric		Gas		Demand	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
EMCS	1.47		25.94		0.12	
Cooling Tower VFD Fan Control	0.64				0.06	
VFD for Supply Fans	0.15					
VAV w/ hot water reset	2.01		30.21		0.38	
Total—Dynamic EEMs	4.27		56.15		0.56	
Savings From Direct & *Indirect* Corrections						
Cooling Tower VFD Fan Control						
Cooling Tower VFD Enabled	0.09	13				
VFD for Supply Fans						
Relief Fan VFD Added and Enabled	*0.13*				*0.10*	
Total—Direct Corrections	0.09	2				
Total—*Indirect Corrections*	*0.13*				*0.10*	
Savings From Unrelated Corrections						
Stuck Open VAV Box Repaired	0.15		0.88		0.16	
Stuck Cooling VAV Box Repaired	0.06		2.65			
Total—Unrelated Corrections	0.21		3.53		0.16	
Total—All Corrections	0.42		3.53		0.26	

Office Building E

This building had six EEMs as shown in Table 4.6. We quantified the benefits of three deficiences, although there were many non-energy benefits and outstanding, or uncorrected deficiences noted in the documentation.

At the time of commissioning, only the 6th floor was occupied, and some EEM-related work was not completed on the other floors. The 6th floor lighting control was found to be set as one zone for the whole floor, and it was changed to four zones. The CA instructed the electrical contractor to make this change on all of the floors. The EEM modeling assumes that the lighting sweeps have the effect of reducing on-time for all lighting by two hours per day. The modeling suggests up to five zones per floor with individual overrides, plus a floor-wide override for cleaning. The baseline assumptions are often incomplete for judging the design intent. We assumed that the one-zone per floor would obtain about half of predicted savings from the original DOE-2 model.

The CA found problems with the static pressure reset control on 1st and 5th floors of this six story building. The reset control allows the fan to run at a lower pressure, thereby saving energy. After several attempts to compile the fan curves from the manufacturer we developed an estimate of the energy savings by making a change in the duct static pressure within DOE-2. This resulted in minor savings.

The CA also found that the cooling tower fan VFD was not interlocked with the condenser pump. In the evening, when compressor cooling was not called for, the tower fan was running, rising from about 1 to nearly 15 amps as measured by the CA. The tower was trying to achieve indoor stagnant loop temperature of 75 °F. Extrapolating from short-term measurements to annual savings, the correction saved 0.21 kWh/ft^2-yr.

A few other problems are worth noting. One minor deficiency that was corrected was a problem with the condenser water pump VFD. The VFD apparently was not working and the water pump pressure transmitter was selected for the wrong range. Correction of this problem might have saved up to 0.31 kWh/ft^2-year, but these savings were not claimed because the documentation on the problem and technical details are limited (Kaplan, 1995). A problem with the chiller reset control was not corrected. The chiller does not operate efficiently at light loads because of poor modulating capability.

As the table shows, natural gas used for heating increased with several of the deficiency corrections. This was a common finding in many of the buildings, as shown further below.

Table 4.6. EEM and Commissioning Energy Savings for Building E.

	Electric		Gas		Demand	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Occupancy Sensors	0.13		-0.01		0.03	
VFD Condenser Pump	0.31					
EMCS	1.4		2.47		0.08	
VFD Supply/Return Fans	1.43		-1.93		0.11	
VFD Cooling Tower Fan	0.09				0.02	
VFD Hot Water Pumps	0.13		0.91		0.02	
Total—Dynamic EEMs	3.48		1.42		0.24	
Savings From Direct & *Indirect* Corrections						
EMCS						
Lighting Sweeps Rezoned	0.25	18	-0.22	-8	0.01	16
VFD Supply/Return Fans						
Static Pressure Reset Fixed	*0.05*		*-0.03*		*0.02*	
VFD Cooling Tower Fan						
Cooling Tower Fan Interlock Fixed	0.21	227				
Total—Direct Corrections	0.46	13	-0.22	-15	0.01	5
Total—*Indirect Corrections*	*0.05*		*-0.03*		*0.02*	
Total—All Corrections	0.51		-0.25		0.03	

Office Building F

The EEMs at this office building included an EMCS and VAV with VFDs (Table 4.7). We estimated energy savings for four deficiency corrections.

The first correction involved enabling the night purge control within the EMCS. This was estimated using DOE-2. It was part of the original DOE-2 analysis.

The second problem corrected was a static pressure sensor that caused the relief fan VFDs to malfunction. The fan was not functioning up to its proper speed, and was running at a minimum speed. The energy savings were estimated outside of DOE-2 because the design model did not include a relief fan. We assumed that the problem would be significant during economizer operation and that the fan has a modestly lower capacity than the supply fan. Furthermore, we assumed that the non-functioning relief fan added 20% to the static pressure across the supply fan face. This reduced the air flow and some of the economizer benefit is lost. The net effect was a slight increase in electricity consumption. This is the only deficiency correction we examined that resulted in a net, though small, increase in energy use.

The third problem involved repairing the lighting sweep controls. Had the CA not been involved it is quite likely that the non-functioning sweeps would never have been repaired because he alone continued to pester the contractor (Kaplan, 1995). To be conservative we allotted half of the savings from the lighting sweep controls to the commissioning, although the savings may have been 100%. These savings were estimated using DOE-2.

The fourth problem involved correcting severe fluctuations in the discharge air temperature. This problem was identified from examining EMCS trend logs. Such fluctuations reduce the cooling efficiency because of thermal losses from compressor cycling. To estimate the energy savings we modeled a 10 percent decrease in the COP within DOE-2.

Several additional minor problems, such as bad VAV box flow sensors were also found.

Although the energy savings estimates for three of the four deficiency corrections were developed using DOE-2, the savings estimates for commissioning are not directly comparable to the design estimates because of apparent errors in the original DOE-2 model. The most significant problem was that there were no HVAC control improvements in the EMCS parametric simulation run. Rather, the EMCS was modeled in a simplistic fashion by changing the lighting schedule. A related problem was that the night purge control was included in VAV parametric, not in the EMCS parametric. A third problem involved an error in the translation of the DOE-2 results into the final energy savings tables; gas consumption increased with the VAV parametric, but it was not reported in the EEM summaries. The tables listed in this report were corrected.

Table 4.7. EEM and Commissioning Energy Savings for Building F.

	Electric		**Gas**		**Demand**	
	kWh/ft²yr	*% of EEM*	*kBtu/ft²yr*	*% of EEM*	*W/ft²mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
EMCS	1.24		-1.51			
VAV w/VFD	2.27		-14.92		0.75	
Total—Dynamic EEMs	3.52		-16.43		0.75	
Savings From Direct & *Indirect* Corrections						
EMCS						
Night Cooling Purge Fixed	0.02					
Discharge Air Temp. Swings Minimized	0.09	7			0.07	
Lighting Sweep Zoning	*0.62*		*-0.75*			
VAV w/VFD						
Malfunctioning Press. Sensor Replaced	-0.02	0				
Total—Direct Corrections	0.08	2			0.07	10
Total—*Indirect Corrections*	*0.62*		*-0.75*			
Total—All Corrections	0.70		-0.75		0.07	

Office Building G

There were five deficiency corrections at Building G for which energy savings estimates were developed.

The first correction involved enhancements to the EMCS, including an optimal stop, or coast-down control. To model the energy savings from this correction we relaxed zone temperature setpoints in the final two hours of occupancy within DOE-2.

The second correction improved the zoning of the lighting sweeps. The CA indicated to LBL that they improved the zoning for the sweeps from one zone to many zones per floor. This change results in the use of fewer lights during unoccupied hours. We estimated the savings within DOE-2 by changing the nighttime lighting hours of use, assuming there would be savings one night in three. PacifiCorp's Commissioning Technical Coordinator recalls that the problem was more severe than our estimate of savings suggests. He recalled that the physical zones and the control overrides were poorly matched. The energy savings from the lighting sweeps might have been 100% defeated by frustrated occupants and operators. The savings are then about three times greater than those listed in Table 4.8.

Table 4.8 EEM and Commissioning Energy Savings for Building G.

	Electric		**Gas**		**Demand**	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Occupancy Sensors	0.57					
EMCS	4.48		-5.27		0.90	
Variable Speed Fans (VFD w/VAV)	1.98				0.37	
Daylighting	0.51				0.14	
Total—Dynamic EEMs	7.53		-5.27		1.41	
Savings From Direct & *Indirect* Corrections						
EMCS						
EMCS Coast Down Added	0.25		0.03		-0.03	
Lighting Sweeps Rezoned	*0.56*		*-0.09*			
Reheat Fans Enabled	*0.27*		*0.04*			
Supply Air Reset Modified	1.70	38	0.61	-10		
Daylighting						
Daylighting Sensors Modified	0.51	100			0.14	100
Total—Direct Corrections	2.46	33	0.64	-11	0.10	7
Total—*Indirect Corrections*	*0.83*		*-0.06*			
Total—All Corrections	3.30		0.57		0.10	

The third correction involved enabling proper operation of the reheat fans, which were found to be controlled incorrectly. There are 3 stages of heating available. The first stage consists of reducing the VAV box position to a minimum to reduce the supply air volume. The second stage involves adding warm return air in the supply mix, which is done with a fan-powered induction unit. The third stage uses electric resistance heat in the mixing box. We estimated the energy savings using DOE-2 by comparing the energy use with fan powered induction units to a standard VAV configuration that does not use induction units.

The fourth correction involved a change in the control method to reset cool supply air (Table 4.8). We used DOE-2 to estimate a change from constant to warmest zone control.

This was the same control sequence change used in the design prediction to evaluate the energy savings of the EMCS EEM. The actual problem, which was slightly different, involved using return air temperatures to reset the supply air temperature, causing fighting between the heating and cooling system during morning warm up. DOE-2 cannot be used to directly model the problem.

Energy savings for the fifth correction, repairing the daylighting, were taken directly from the design study estimate. The manufacturers had to add a cone around the daylighting sensors to register changes in daylight because the dark carpet interfered with their operation.

Office Building H

This building is the largest building, and the only retrofit. The commissioning agents were also the retrofit construction managers. They are known for their innovative practices including careful commissioning of EMCS, extensive post-retrofit monitoring, and state-of-the art control software, The control strategy is known as terminal-regulated air volume (TRAV, as listed in Table 4.9). It is likely that our energy savings estimates for commissioning greatly underestimate its value. Throughout the extensive reports on this project the CA mentions that it is difficult to distinguish between monitoring and commissioning activities because the monitoring was used to verify the performance of the retrofit.

Since it was a retrofit there were tests to identify pre-existing problems. About 40 percent of the VAV boxes had calibration problems. Poor calibration could lead to occupant complaints and control difficulties, but may result in more or less energy use. These problems may be a wash on energy impacts, though clearly there are non-energy benefits from improving zone control. The CA also found problems with hot-cold VAV box flapper operation, such as disconnected dampers and flappers that don't seal, causing leaks in the VAV mixing boxes.

There were extensive leaks found in the ductwork, some which were repaired by the owner. To model this change we increased the fan kW and decreased the air flow to assume that the W/cfm increased, resulting in the savings shown in Table 4.9. The CA also found that the air flow for one floor of the 16-story building was left out of air-flow requirement calculation within the controls. This was corrected. If the are flow on the floor that was left out of the averaging was significantly different than the others there could be a significant difference in total fan flow control setting.

The CA found that the lighting sweeps were problematic on several floors. Hardware switches bypassed about 5 percent of the lights, which would have resulted in 24-hour use. Savings from this deficiency correction are quantified. The CA also found that both the mixed air damper and the chiller short-cycled. Short cycling could lead to early equipment failure. We quantified the energy savings from reducing the chiller cycling by estimating that the efficiency was reduced by 10 percent.

Table 4.9. EEM and Commissioning Energy Savings for Building H.

	Electric		Gas		Demand	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
TRAV	8.67				3.04	
Total—Dynamic EEMs	8.67				3.04	
Savings From Direct & *Indirect* Corrections						
TRAV						
Chiller Cycling Reduced	*0.21*				*0.04*	
Total—Direct Corrections						
Total—*Indirect Corrections*	*0.21*				*0.04*	
Savings From Unrelated Corrections						
Duct Leaks Repaired	0.07				0.01	
Total—Unrelated Corrections	0.07				0.01	
Total—All Corrections	0.27				0.05	

Theater Building I

Building I, a partially occupied movie cinema, is the smallest building in this study. The programmable thermostat was found to be working correctly, but the economizers were not (Table 4.10). Poorly calibrated outdoor air thermostats limited the effectiveness of all five units, causing them to cut out at 60 °F rather than 70 °F. This was modeled directly with DOE-2. Several other problems were encountered and corrected, such as a bad damper seal and dead circuit boards. This economizer EEM was almost completely defeated without commissioning.

Table 4.10. EEM and Commissioning Energy Savings for Building I.

	Electric		Gas		Demand	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Programmable Thermostat	0.01		0.40			
Economizer plus Ventilation Control	0.59		0.88		0.08	
Total—Dynamic EEMs	0.60		1.28		0.08	
Savings From Direct & *Indirect* Corrections						
Economizer plus Ventilation Control						
Economizer Setting Limited	0.44					
Economizer Circuits Corrected	0.10	18				
Total—Direct Corrections	0.54	91				
Total—All Corrections	0.54					

Retail Building J

The only dynamic EEM in this fabric store was the economizers (Table 4.11). The CA reported several problems. Two of the systems had missing parts, one had with a bad control board, and the other was not wired properly. After those corrections were made there were still problems. One system hunted, which means that dampers opened and closed trying to find a stable position under the control sequences specified. Hunting can destroy linkages because of over use. The other system was repaired after the damper motor fell off a bracket. These problems would essentially have defeated the economizers. The commissioning agent also tested the occupancy sensors and found them to be working correctly.

The energy savings from correcting the economizers (Table 4.11) amounts to 55% of the original EEM estimate for the economizers. The reason that the savings for correcting the economizers are not 100% of the predicted EEM savings is because of the difference between interactive and parametric savings. This difference is accounted for in the whole building energy savings estimates discussed below in Chapter 5, and the ratio for savings from commissioning compared to the total EEM savings increased from 12% to 18%.

Table 4.11. EEM and Commissioning Savings for Building J.

	Electric		Gas		Demand	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Occupancy Sensors	0.46		-0.99		0.06	
Economizers	0.22					
Total—Dynamic EEMs	0.69		-0.99		0.06	
Savings From Direct & *Indirect* Corrections						
Economizers						
Economizer Hardware Repaired	0.12	55			0.03	
Total—Direct Corrections	0.12	18			0.03	50
Total—All Corrections	0.12				0.03	

Retail Building K

This strip mall is one of two buildings for which we have no quantified energy savings (Table 4.12). The commissioning report mentioned a minor deficiency: a valve on an air handling unit was sized incorrectly. However, it is unclear if anything was done. Another issue was that the CA noticed that a weekday, weekend (5-1-1) thermostat was installed instead of the specified 7-day setback thermostat. This is a fairly trivial difference in the controls. Only 4 of 15 heat pumps were fully installed when the commissioning took place. The commissioning activities might have been more productive if they had taken place after the building construction was more complete.

Table 4.12. EEM and Commissioning Energy Savings for Building K.

	Electric		Gas		Demand	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Efficient Heat Pumps	0.47				0.06	
Programmable Thermostats	0.29				-0.05	
Total—Dynamic EEMs	0.77					
Savings From Direct & *Indirect* Corrections						
Total—Direct Corrections						
Total—All Corrections						

Grocery Building L

This building is one of the two grocery stores in this study. The CA found rapid cycling of the compressors on one of several refrigeration racks. This was modeled by reducing the COP by 15 percent. Left uncorrected, this deficiency could have had severely reduced the equipment lifetime. The controls for the anti-condensate system on the refrigation case doors were also repaired. The savings from this correction were estimated using DOE-2 and are a subset of the refrigeration EEM shown in Table 4.13, although not separately considered in the parametric analysis in of the design study. The Technical Coordinator also noted that the floating head pressure control was not optimized, the programmable thermostat was bypassed, and its clock incorrectly set. We did not find discussion of the latter issue in the CA's report.

Table 4.13. EEM and Commissioning Energy Savings for Building L.

	Electric		**Gas**		**Demand**	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Efficient Refrigeration	25.27		0.21		2.99	
EMCS	2.24		1.65			
Total—Dynamic EEMs	27.50		1.86		2.99	
Savings From Direct & *Indirect* Corrections						
Efficient Refrigeration						
Refrigeration Equip. Cycling Reduced	*0.85*				*0.12*	
Anti-Sweat Controls Repaired	3.53	14			0.42	14
Total—Direct Corrections	3.53	13			0.42	14
Total—*Indirect Corrections*	*0.85*				*0.12*	
Total—All Corrections	4.38				0.54	

Hospital Building M

Occasionally the commissioning activities are conducted under a fast schedule, which can result in scaling down the scope of work. This hospital was such a case. The CA found several deficiences at the building site, but was not funded to follow up to ensure that the deficiences were corrected. There are no energy savings estimates for commissioning at this site. It is likely that some savings were achieved.

Table 4.14. EEM and Commissioning Energy Savings for Building M.

	Electric		**Gas**		**Demand**	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Occupancy Sensors	0.26				0.09	
EMCS	1.16				0.26	
High Eff. AC	0.05				0.09	
Total—Dynamic EEMs	1.46				0.44	
Savings From Direct & *Indirect* Corrections						
Total—Direct Corrections						
Total—All Corrections						

Motel Building N

This motel was fully occupied early after it opened and the CA had to rent two rooms to conduct the commissioning tests. The CA found that the 15 amp cables used for the heat pump system were too small for the proper operation of the heat pumps, which were changed to 20 amp cables. The undersized cables resulted in excessive use of electric resistance heat because the effectively downsized heating system could not maintain comfortable temperatures. Energy use decreased because of the reduced use of resistance heating (Table 4.15).

The second EEM correction fixed a three-way valve on a pool dehumidifier heat recovery system. Replacing the valve eliminated the periodic over-heating and modification of the control setpoints reduced condensation. The energy savings from this correction were extrapolated from monitored electricity use data. This pool dehumidifier EEM is primarily a gas saving measure, or perhaps more appropriately considered a fuel-switching measure. as shown in Table 4.15. The predicted electricity savings were extremely small (0.01 kWh/ft^2-year). The savings from commissioning were nine times greater than the predicted electricity savings from the EEM.

In both cases the motel suffered from HVAC systems that would cause discomfort to guests, perhaps reducing their likelihood of returning. At least one guest actually left the motel because of the low indoor temperatures. We estimate that the lost-revenue from reduced room rentals would have amounted to an additional $500/year (further discussed in Chapter 5).

Table 4.15. EEM and Commissioning Energy Savings for Building N.

	Electric		**Gas**		**Demand**	
	kWh/ft^{2}yr	*% of EEM*	*kBtu/ft^{2}yr*	*% of EEM*	*W/ft^{2}mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Efficient PTAC Heat Pumps	0.08					
Split Heat Pumps	0.46					
Pool Dehumidifier Heat Recovery	0.00		10.34			
EMCS	0.62		0.03		0.07	
Total—Dynamic EEMs	1.17		10.38		0.07	
Savings From Direct & *Indirect* Corrections						
Efficient PTAC Heat Pumps						
PTAC Resistance Heat Fixed	*0.17*				*0.03*	
Pool Dehumidifier Heat Recovery						
Pool Dehumidifier Repaired	0.03	926				
Total—Direct Corrections	0.03	3				
Total—*Indirect Corrections*	*0.17*				*0.03*	
Total—All Corrections	0.20				0.03	

Grocery Building O

Building O is a grocery store with extensive refrigation, HVAC, and lighting EEMs. Unlike at Grocery L where all of the commissioning fixes were related to the refrigeration systems, all of the commissioning fixes at Grocery O are related to the HVAC and lighting systems.

There were several issues found during commissioning that concerned the controls. The installed controls differed greatly from the early conceptual design for an integrated EMCS. The refrigation, HVAC, and lighting controls were separate rather than integrated. The CA found that neither the lighting nor the HVAC controls were properly programmed for unoccupied hours. Our estimate of the savings from the reprogramming is shown in Table 4.16. The DOE-2 modeling of the improved equipment schedules was straightforward. Heating, cooling, and HVAC auxiliary energy use was reduced.

As with other sites, there were problems with the economizers. In this case problems with air temperature sensors defeated the control logic. An interesting angle to this building is that the economizer on the larger HVAC unit was not a funded EEM, but was required by code. The economizers on the two smaller units were funded EEMs. We therefore separated the deficiency into two categories: 1) fixing the EEM (a direct correction) and 2) fixing the larger economizer (an indirect correction).

Table 4.16. EEM and Commissioning Energy Savings for Building O.

	Electric		Gas		Demand	
	kWh/ft²yr	*% of EEM*	*kBtu/ft²yr*	*% of EEM*	*W/ft²mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
High Eff. AC Unit	0.04				0.03	
Occ. Lights Controls	0.30		-0.15		0.34	
Unequal Parallel Compressors	2.50				0.44	
Refr Heat Recovery	0.26		1.48		0.05	
Anticondensate Controls	0.26				0.05	
Freezer Doors	3.99		6.73		0.68	
Floor Return Air Duct	0.45		-7.55		0.16	
Economizer Cycle	0.77				0.05	
EMCS	2.88		-8.56		0.03	
Total—Dynamic EEMs	11.46		-8.07		1.82	
Savings From Direct & *Indirect* Corrections						
Economizer Cycle						
Economizers Fixed	0.64	83			0.08	145
Large Economizer Fixed	*0.47*		*0*		*0.05*	
EMCS						
Lighting Controls Reset	2.34		-7.51		0.02	
HVAC Unoccupied Control	0.00	0.00	4.42	-51	-0.02	-129
Total—Direct Corrections	2.98	26	-3.1	38	0.06	4
Total—*Indirect Corrections*	*0.47*		*0.00*		*0.05*	
Total—All Corrections	3.45		-3.1		0.12	

Hotel Building P

This hotel is similar to Retail K and Hospital M in that there was little information on deficiency corrections in the final commissioning report. In fact, the single deficiency we quantified was not mentioned in the CA's commissioning summary, but was found in an appendix of the final report. The problem involved a damper and cooling tower fan motor that caused the cooling tower water temperature to increase, which we modeled as a 10 percent decrease in the cooling COP. The problem occurred for 45 hours over a four month period, and was unrelated to the EEMs. The Technical Coordinator also reported a problem with sludge and scale in the hydronic heat pump loop that was not documented as corrected.

Table 4.17. EEM and Commissioning Savings for Building P.

	Electric		Gas		Demand	
	kWh/ft²yr	*% of EEM*	*kBtu/ft²yr*	*% of EEM*	*W/ft²mth*	*% of EEM*
Predicted Savings From Dynamic EEMs						
Heat Pumps	0.05				0.95	
EMCS	2.34				-0.11	
Total—Dynamic EEMs	2.39				0.82	
Savings From Direct & *Indirect* Corrections						
Total—Direct Corrections						
Savings From Unrelated Corrections						
Cooling Tower Failure Repaired	0.03				0.00	
Total—Unrelated Corrections	0.03				0.00	
Total—All Corrections	0.03				0.00	

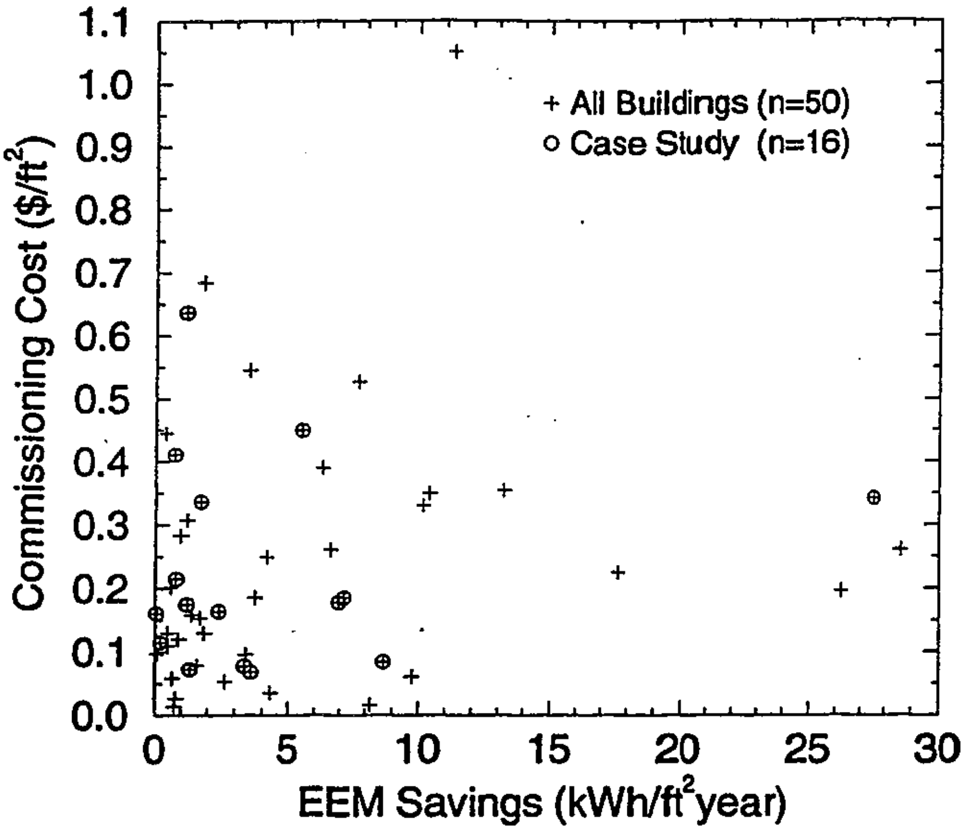

Figure 4.1. Commissioning costs versus predicted dynamic EEM savings. The costs for commissioning in these 16 buildings is similar to the large sample from PacifiCorp, with an average of $0.23/ft^2 in both samples.

5. Results Among Buildings

This section discusses the energy savings and economics among all 16 buildings at the whole-building level. The savings for each deficiency correction were described in detail in Section 4.

Energy Savings Among Buildings

Table 5.1 shows the total energy savings from the dynamic EEMs for each building, and the total energy savings from commissioning. All three categories of deficiency corrections are included: direct, indirect, and unrelated. Electricity savings from commissioning vary from zero to 4.4 kWh/ft^2-yr, with an average of 0.97 kWh/ft^2-yr. The average is somewhat skewed by the high savings at Buildings L. There were no quantified savings at Buildings K or M. All sixteen buildings are included in the averages. The median savings were 0.47 kWh/ft^2-yr.

Several of the EEMs and related deficiency corrections caused an increase in gas consumption, but there are no net losses in energy use. The six buildings with no EEM gas savings are all electric.

Table 5.1. Annual Energy Savings from Dynamic EEMs and Commissioning.

Code	Type	Area	Dynamic EEM Savings			Correction Savings		
			Elec.	Gas	Dem.	Elec.	Gas	Dem.
		(kft^2)	*(kWh/ft^2)*	*(kBtu/ft^2)*	*(kW/ft^2)*	*(kWh/ft^2)*	*(kBtu/ft^2)*	*(kW/ft^2)*
A	Office	19.8	2.88		2.73	0.04		0.02
B	Office	21.8	1.74		0.18	1.09		0.57
C	Office	24.8	0.07	121.93	0.20	0.22	1.42	
D	Office	34.0	4.27	56.15	0.56	0.42	3.53	0.26
E	Office	66.0	3.48	1.42	0.24	0.51	-0.25	0.03
F	Office	66.4	3.52	-16.42	0.75	0.70	-0.75	0.07
G	Office	84.1	7.53	-5.26	1.42	3.30	0.57	0.10
H	Office	312.0	8.67		3.04	0.56		0.03
I	Theater	12.5	0.60	1.28	0.08	0.54		
J	Retail	17.0	0.69	-0.93	0.06	0.12		0.03
K	Retail	17.0	0.77					
L	Grocery	19.4	27.5	1.86	2.99	4.38		0.54
M	Hospital	23.0	1.46		0.44			
N	Motel	29.0	1.17	10.38	0.07	0.20		0.03
O	Grocery	38.5	11.46	-8.04	1.82	3.45	-3.10	0.12
P	Hotel	64.5	2.39		0.82	0.03		0.00
Avg		53.0	4.85	10.15	0.96	0.97	0.09	0.11

Blank data are zero values, which are included in the averages.

The ratio of the commissioning correction savings to the EEMs savings were shown for each building by EEM in the tables of Section 4. Table 5.2 shows the ratio of the total savings from commissioning to the total dynamic EEM savings at the whole-building level based on data in Table 5.1. These ratios are useful to understand the relative magnitude of savings from commissioning compared to the predicted EEM savings. The electricity ratios range from zero to 2.93, with an average of 0.39. On the high end of the range, the electricity savings from commissioning at Building C were nearly three times as much as the predicted savings. But, as mentioned in Section 4, this is a misleading comparison because the EEM was oriented toward saving gas, not electricity. When Building C is excluded the average ratio of correction savings to EEM savings is 0.22.

The final column of Table 5.2 shows the electricity savings ratio adjusted to consider the difference between interactive and parametric savings. The ratio between interactive and parametric savings used to make the adjustments are shown in Table 5.3. For most buildings this adjustment increased the ratio of commissioning to EEM savings. The average ratio is 0.41 with the zero values included. That is, 41 percent of the EEM savings would not have been present without commissioning. The average without Building C is 0.24 and the median is 0.18.

The Energy FinAnswer program was focused on electricity savings measures. The peak demand savings ratio ranged from zero to 3.12, with an average of 0.32.

Table 5.2. Ratio of Whole-Building Savings from Commissioning to EEMs.

Code	Correction/EEM			Interactive/Param. Adjusted
	Electricity	Gas	Peak Demand.	Electricity
A	0.01		0.01	0.02
B	0.63		3.12	0.71
C	2.93	0.01		3.07
D	0.10	0.06	0.47	0.15
E	0.15	-0.17	0.14	0.17
F	0.20	0.05	0.10	0.09
G	0.44	-0.10	0.07	0.34
H	0.06		0.01	0.06
I	0.91			1.05
J	0.18		0.50	0.21
K				
L	0.16		0.18	0.16
M				
N	0.17		0.40	0.19
O	0.30	0.39	0.06	0.35
P	0.01		0.01	0.01
Avg	0.39	0.01	0.32	0.41
AvgNoC	0.22	0.01	0.34	0.24

As shown in Table 5.3, about half of the energy savings from deficiency corrections were direct savings. That is, of the total energy savings from commissioning, about half of those energy savings are directly related to the EEMs. These savings are the percentages of the present value of the energy cost savings which allow us to compare electricity, gas, and peak demand savings together.

Three buildings had savings categorized as unrelated (Buildings D, H, and P). That is, the deficiency that was corrected during commissioning was not related to the EEM. For example, the unrelated savings at Building P were from an cooling tower problem that was not related to the EEMs. Since it was the only deficiency at the site, the unrelated savings were 100 percent of the commissioning savings.

One interesting aspect of the savings by type of correction (direct, indirect, and unrelated) is the difference in savings by building size. The buildings where the savings were all direct (100 percent) were small buildings (Buildings A, F, I, J, and O). This is understandable because building systems in large buildings are often more integrated. Therefore, the commissioning of EEMs in smaller buildings is more isolated to a particular system than in larger buildings. This is an important finding for designing commissioning requirements, and may suggest some categorizations that relate building size to building system integration.

Table 5.3. EEM Savings Ratios and Corrections by Type.

Code	Area	Inter./Para. Ratio[a]		Percentage of Correction Dollar Savings (%)					
				Direct		Indirect		Unrelated	
	(kft^2)	kWh	PV	low	high	low	high	low	high
A	19.8	0.98	0.92	100	100				
B	21.8	0.89	0.88	7	15	93	85		
C	24.8	0.96	1	53	53	47	47		
D	34	0.64	0.66	7	7	24	24	69	69
E	66	0.84	0.86	95	84	5	16		
F	66.4	2.12	1.99	27	27	73	73		
G	84.1	1.27	1.29	77	78	23	22		
H	312	1.01	1.02			81	86	19	14
I	12.5	0.87	0.78	100	100				
J	17	0.84	0.86	100	100				
K	17	0.94	0.96						
L	19.4	0.97	0.97	80	80	20	20		
M	23	0.93	0.9						
N	29	0.92	0.94	14	14	86	86		
O	38.5	0.87	2.71	83	83	17	17		
P	64.5	0.87	0.84					100	100
Avg.	53.1	0.99	1.1	46	46	29	30	12	11

[a] A ratio below one means that the combined effect of all EEMs (interactive savings) is less than the sum of all the individual parametric EEM savings. The kWh value is the electricity savings alone; the PV value is the dollar savings including demand and gas savings (sometimes negative).

It is useful to examine the savings from direct commissioning fixes separately from the total savings. Table 5.4 shows the energy savings and savings ratio to the EEM savings for the direct corrections only. The average savings from direct deficiency corrections was 19 percent of the predicted EEM savings. This is less than the average of 24 percent for all categories (direct, indirect, and unrelated) commissioning corrections shown in Table 5.2. The gas and peak demand ratios are also lower (than those listed for all correction in Table 5.2) with average of 0.01 and 0.09 respectively. Median gas and peak demand savings are zero.

Table 5.4. Savings from EEMs and Direct Deficiency Corrections.

Code	Direct Correction Savings			Correction/EEM			Int./Param.
	Elec. *(kWh/ft²)*	Gas *(kBtu/ft²)*	Dem. *(kW/ft²)*	Elec. *Elec.*	Gas	Dem.	Adjusted
A	0.04		0.02	0.01			0.02
B	0.30			0.17			0.2
C	0.04	1.42		0.54	0.01		0.57
D	0.09			0.02			0.03
E	0.46	-0.22	0.01	0.13	-0.14	0.06	0.16
F	0.08		0.07	0.02		0.10	0.01
G	2.46	0.64	0.1	0.33	-0.11	0.08	0.26
H							
I	0.54			0.91			1.05
J	0.12		0.03	0.18		100	0.21
K							
L	3.53		0.42	0.13		0.14	0.13
M							
N	0.03			0.03			0.03
O	2.98	-3.10	0.06	0.26	0.38	0.04	0.30
P							
Avg	0.67	-0.07	0.04	0.17	0.01	0.09	0.19

Non-Energy Savings Benefits

There are important benefits from commissioning that go beyond energy savings. We have tracked four general categories of non-energy benefits, and several additional types of benefits lumped into a miscellaneous category. These benefits are assigned to deficiency corrections that were not quantified in the energy savings analysis. Many of the deficiences for which we developed energy savings estimates also have non-energy benefits that are also tracked, as listed in Tables 5.5 and 5.6.

A total of 73 corrections were tracked among all 16 buildings. The first table of non-energy savings benefits (Table 5.5) lists corrected deficiences that involved hardware changes. The second table (5.6) lists corrections that involved changes to software and control settings. There is not always a clear distinction between the hardware and software fixes, but the rationale for distinguishing between the two is the fact that software changes might be less costly to correct because no additional hardware are needed. This suggests the need for careful documentation on control settings.

Most of the corrections were related to HVAC systems, with the remaining related to lighting and one related to refrigeration equipment. The four categories of non-energy benefits defined in Section 3 are:

- Improved Controls and Zoning (CON)
- Improved Equipment Life (EQT)
- Improved Operations and Maintenance (O&M)
- Improved Indoor Environmental Quality and Comfort (IEQ)

One of the additional miscellaneous benefits is the reduction in spending within the Energy FinAnswer program that occurred when the commissioning agent reported that an installed measure or building system differed greatly from design. Tables 5.5 and 5.6 do not list the five instances of reduced EEM dollars.

In total, 67 deficiency corrections are listed in the tables that were not quantified. Six others miscellaneous benefits were tracked: five deficiences involved reducing the EEM funding, and one correction improved the quality of frozen foods.

Table 5.5. Non-Energy Benefits from Hardware Changes.

	Bldg Code	Quantified[a]	Non-Energy Benefit Code CON	EQT	O&M	IEQ
HVAC Deficiency Corrections						
Installed Missing Thermostat	A		C			I
Static Pressure Reset Fixed	E	Q	C			I
Electrical problems on VFD Fixed	E			E		
Supply Fan VFD Phase Currents Unbalanced	D			E		
Discharge Sensor Missing	O			E		I
EMCS Adapter Cable Fixed	G				O	
Economizer Circuits Corrected	I	Q		E	O	
Malfunctioning Press. Sensor Replaced	F	Q		E		
Reheat Fans Enabled	G	Q			O	
Resistance Heat Reduced	B	Q	C		O	
T-stat Added	G		C			I
T-stat Slider Fixed	G		C			I
Thermostat Replaced or Calibrated	E		C		O	I
Thermostats Relocated	D		C			I
VAV Box Flow Sensor Replaced	F		C		O	I
Compressor Shipping Block Removed	O			E		I
Condenser Pump Leak Repaired	D				O	
Damper Failure to Shut Fixed	G			E	O	
Duct Obstruction Removed	G					I
Economizer Dampers Repaired	B	Q		E	O	I
Economizer Hardware Repaired	J	Q	C	E	O	
Fan Grease Ports Located	D			E	O	
Filter Cleaned	N				O	I
Filters Changed; Refrigerant Charged	B	Q	C			I
Heat Wheel Aligned	C	Q		E	O	
PTAC Resistance Heat Fixed	N	Q	C		O	
Pool Dehumidifier Repaired	N	Q	C	E	O	I
Relief Fan VFD Added and Enabled	D	Q	C		O	I
Selected VAV Boxes Balanced	G					I
Stuck Cooling VAV Box Repaired	D	Q	C			I
Stuck Open VAV Box Repaired	D	Q	C			I
Supply Fan Damper Adjusted	D			E		
VAV Box Access Improved	G				O	
Economizer Setting Limited	I	Q		E	O	
Lighting Deficiency Corrections						
Daylighting Sensors Modified	G	Q		E	O	

[a] Energy savings were also estimated.

Table 5.6. Non-Energy Benefits from Software Changes.

	Bldg Code	Quantified[a]	Non-Energy Benefit Code			
			CON	EQT	O&M	IEQ
HVAC Deficiency Corrections						
Airflow Algorithm Corrected	H		C			
Cooling Tower Fan Interlock Fixed	E	Q	C	E		
Water Loop Control Adjusted	A		C			
Condenser Water VFD Control Fixed	E				O	
Static Pressure Adjusted	G					I
Heat Wheel Control Improved	C	Q				I
VAV Boxes Tuned	H		C		O	I
After Hour Override Enabled	E		C		O	
Air Damper Cycling Reduced	H		C	E	O	
Cooling Tower VFD Enabled	D	Q			O	
Discharge Air Temp. Swings Minimized	F	Q		E		
EMCS Coast Down Added	G	Q		E	O	
EMCS Zone Descriptions Improved	D		C		O	
HVAC & Lights Hour Use Enabled	F		C			I
HVAC Timeclock Reset to PST	L		C			
HVAC Unoccupied Control	O	Q		E		
Heat Wheel DDC Control Improved	C	Q	C			I
Minimum OSA Programming Added	F		C		O	I
Night Cooling Purge Fixed	F	Q	C			I
Supply Air Reset Modified	G	Q			O	
Chiller Cycling Reduced	H	Q	C	E	O	
Lighting Deficiency Corrections						
Daylight Dimming Adjusted	A	Q			O	
Lighting Circuit Timeclock Corrected	L				O	
Lighting Sweep Zoning	F	Q	C			
Lighting Sweeps Rezoned	E	Q		E		
Lighting Sweeps Rezoned	G	Q		E	O	
Occupancy Sensors Adjusted	J		C		O	
Refrigeration Deficiency Correction						
Refrigeration Equip. Cycling Reduced	L	Q		E		

[a] Energy savings were also estimated, as shown in Section 4.

Qualitative Examples of Non-Energy Benefits

Throughout the report we have mentioned some of the non-energy benefits of commissioning. We present some additional examples to touch again on these concepts. There were several important non-quantified deficiency corrections at almost every building. The examples suggest that the problems encountered are often significant and perhaps even severe.

- At Building D, the outside air damper was adjusted, thermostats were relocated, and EMCS zone descriptions improved, all of which should contribute to operational, control, and indoor comfort improvements. Special attention was needed to identify ports for greasing the fan as part of future maintenance. Had these not been located the equipment might have suffered from premature failure. A condensing water pump leak was identified and repaired.
- Commissioning at Building A included repairing a blocked outside air damper and cleaning dirty filters, which result in improved air quality. The CA also found that a fire damper was closed, which blocked air flow through the duct. This illustrates how the CA might find deficiences that improve fire and safety equipment.

- There were two examples of shipping restraints not properly unleashed on rooftop HVAC equipment that caused severe noise and vibration (Buildings G and O.) These units may also have suffered from early failure.

One CA informed us that if an EMCS is not well commissioned, a building operator may not trust the data available to him to make control and scheduling changes. If the building operator is not confident that the system was calibrated and commissioned properly, he may begin to override it, therefore rendering it useless, or at least, much less useful than optimal. It is extremely difficult to quantify the benefits associated with this sort of quality control.

Quantitative Examples of Non-Energy Benefits

We estimated non-energy benefits at two buildings to illustrate that such savings are often significant. At Building C the CA aligned the heat wheel, which prolonged the lifetime of the brushes that direct the air flow. Normally the brushes are replaced every four years. The CA assumed that the brushes would have had to be replaced every year without the improved alignment. The brushes cost about $150 each, with identical costs for labor. We assumed that the annual cost savings would therefore be about $225. This non-energy benefit is included in the cost-effectiveness estimates for this building discussed in the following subsection (and shown in Figure 5.1).

The second non-energy benefit was quantified for Building N. In addition to the energy savings from the deficiency correction that improved the heating system, we assumed that the indoor temperature problems would have caused lost revenue from ten unrented rooms per year. One guest actually left the hotel because of the cold temperatures. We assume $50 per night lost profit ($60 per night revenue and $10 per night marginal cost) for a total of $500 per year.

Cost Effectiveness of Commissioning

In this section we examine the economics of commissioning. The analysis is approached three different ways. First, we report on the cost-effectiveness of predicted EEMs from the design studies. Second, we discuss the cost-effectiveness of commissioning as a stand-alone measure. Third, we discuss the cost-effectiveness of commissioning when combined with the costs and savings for the measures.

Cost-effectiveness of EEMs from Design Predictions

We begin the discussion on economics by looking at the cost-effectiveness of the dynamic EEMs independent of commissioning. The costs, savings, and simple payback of the dynamic EEMs for each building are shown in Table 5.7. These data were developed as part of the Energy FinAnswer design analysis, independent from commissioning, assuming they would perform exactly as expected. The payback times for the package of EEMs range from 0.1 to 22.2 years, with an average of 9.1 years, and a median of 8.0 years. The table also shows the present value of the energy savings from the EEMs, which is about 11 times the annual energy savings. (See Section 3 for the present value calculation methodology.)

Cost-effectiveness of commissioning as a stand-alone measure

The present value of the energy savings from commissioning are also shown in Table 5.7. The low and high estimates of the present value of the correction savings from commissioning are based on the low and high correction lifetime estimates. The indirect and unrelated savings are shown as a subset of the total savings for all corrections.

Table 5.7 Cost Savings for Commissioning and Dynamic EEM Savings.

Code	PV—Correction Savings				Dynamic EEMs			
	All Corrections		Ind.+Unr.[a]		Savings		Cost	SPT
	low ($/ft²)	high ($/ft²)	low ($/ft²)	high ($/ft²)	Annual ($/ft²)	PV ($/ft²)	($/ft²)	(yrs)
A	0.01	0.03			0.30	3.34	2.38	8.1
B	0.33	0.92	0.31	0.79	0.08	0.92	0.64	7.8
C	0.17	0.27	0.03	0.08	0.56	6.39	0.03	0.1
D	0.22	0.57	0.21	0.53	0.46	5.21	1.51	3.3
E	0.06	0.24		0.04	0.16	1.83	1.69	10.4
F	0.13	0.33	0.10	0.24	0.12	1.32	2.10	18.1
G	0.63	1.25	0.15	0.27	0.37	4.20	1.28	3.5
H	0.21	0.27	0.21	0.27	0.55	6.20	3.55	6.5
I	0.02	0.25			0.03	0.40	0.46	13.1
J	0.01	0.08			0.03	0.30	0.18	6.6
K					0.03	0.35	0.49	15.9
L	0.93	2.38	0.19	0.47	1.31	14.78	15.48	11.9
M					0.09	0.99	0.68	7.8
N	0.06	0.13	0.05	0.11	0.10	1.11	0.90	9.2
O	0.59	1.49	0.10	0.25	0.54	6.14	3.27	6.0
P	0.02	0.02	0.02	0.02	0.15	1.70	2.48	16.5
Avg	0.21	0.51	0.10	0.20	0.30	3.45	2.32	9.1

[a] Indirect plus unrelated corrections only, excludes direct corrections

The present value of the correction savings from commissioning are dominated by electricity cost savings. Figure 5.1 shows that the electricity savings ranged from 33 percent to 100 percent of the total savings benefit for each building, with an average of 67 percent. The gas savings were much lower than the electric savings. Gas savings were about one-third of the savings at Buildings B and C. Peak demand savings were significant at several buildings, and were over half of the savings at Buildings K and L. The figure also shows the non-energy benefits included at Buildings C and N. About one-third of the savings at Building C were non-energy benefits.

The average present value of the savings from commissioning was $\$0.21/ft^2$ for the low-lifetime case and $\$0.51/ft^2$ for the high-lifetime case. In the low-lifetime case the present value of the savings is slightly less than average cost for commissioning, which was $\$0.23/ft^2$. In the high-lifetime case the present value of the savings is about twice as large as the commissioning costs. These data are shown in Figure 5.2, which illustrates that commissioning was generally cost effective. The figure shows the present value of the total savings from commissioning compared to the cost of commissioning for each building, and for the average of all 16 buildings. The present value of the energy savings from commissioning are shown as a range based on the high and low lifetime values. The line of equality is shown, representing where the benefits equal the costs. Half of the building's are above the line of equality, showing that the benefits exceeded the costs, and half are below the line[2].

Our interpretation of these results is that commissioning was marginally cost effective based on energy savings alone. It is also important to remember that although there were no savings quantified for two buildings (Buildings M and K), it is likely that there were in fact some savings. We, however, did not find sufficient evidence from the building documentation to develop an estimate. The high present value of the savings for Building L are related to the fact that it is a grocery building, where energy intensities (area normalized), and energy savings intensities tend to be high.

The average payback for commissioning as a stand alone measure in which the cost for commissioning is compared against the total savings from all three categories of commissioning (direct, indirect, and unrelated) was 14 years (Table 5.8 and Figure 5.3). The median simple payback time is much lower at slightly more than 6 years. Five buildings had payback times less than three years.

Another way to present the overall cost effectiveness is to estimate the ratio of the costs for commissioning to the benefits of the EEM or deficiency correction over its lifetime. This ratios compare the present value of the savings to the costs. A value greater than one indicates that the costs were greater than the benefits. These ratios are shown in Table 5.8, indicating that the costs are less than the benefits for only six buildings for the low lifetime scenario. Average and median ratios cost-benefit ratios for the low lifetime scenario are 3.9 and 1.7. Under the high lifetime case the costs are less than the benefits at ten sites, and the average has decreased to 1.4, with a median of 0.83. This comparison demonstrates the sensitivity of the cost-effectiveness of commissioning to the lifetime of the deficiency correction and persistence savings.

Cost-effectiveness of commissioning combined with the EEMs

It is useful to compare the cost-effectiveness of commissioning combined with the EEMs to evaluate the total investment in energy efficiency. The total costs for commissioning plus the dynamic EEMs ranged from $0.2/ft^2 to $15.8 ft^2, with an average of $2.6/ft^2 (first column of Table 5.8). The energy savings benefit from commissioning combined with the total EEM savings assumes the following. First, after commissioning the EEM saves 100 percent of the predicted savings. Second, are additional savings from indirect and unrelated deficiency corrections that were not considered in the original design prediction. When the total costs for the EEMs and commissioning are compared with the energy savings from the EEMs plus additional indirect and unrelated savings the average payback time is 9.6 years, with a median of 9.9 years (Figure 5.4). These payback times are dominated by the payback of the EEM independent of commissioning since commissioning was only 8% of the total costs. So, in general, the simple payback time with the commissioning and EEMs combined is greater than the predicted simple payback time for the EEMs alone. Five buildings had combined payback times less than five years.

The present value of the energy savings for commissioning plus the EEMs is also shown in Table 5.8. The net savings compare the cost for the EEMs plus commissioning with the present value of the energy savings. A positive value indicates that the investment was profitable. Again, the low and high values show the influence of a low and high lifetime estimate. For the low-lifetime case, the net savings are positive for ten of the 16 buildings. The net savings changes from negative to positive savings with the change in lifetime for Building L, moving the total to eleven buildings with benefits greater than costs. On average the savings were $0.98/ft^2 for the low lifetime, and $1.01/ft^2 for the high lifetime.

Table 5.8. Total Cost-Effectiveness of Commissioning.

Code	Dynamic EEMs + Cx[a]					Cx	EEM[b]	Cost/Benefit Ratios			
	Cost	PV Savings		Net Savings		SPT	+Cx	Cx		DynEEM+Cx	
		low	high	low	high		SPT	low	high	low	high
	($\$/\text{ft}^2$)	($\$/\text{ft}^2$)	($\$/\text{ft}^2$)	($\$/\text{ft}^2$)	($\$/\text{ft}^2$)	(yr)	(yr)				
A	2.45	3.34	3.34	0.89	0.89	26.39	8.31	5.99	2.35	0.73	0.73
B	0.98	1.23	1.71	0.26	0.73	4.12	2.50	1.02	0.36	0.79	0.57
C[c]	0.19	6.43	6.47	6.23	6.28	1.39	0.32	0.96	0.59	0.03	0.03
D	1.96	5.42	5.74	3.45	3.77	8.96	2.94	2.02	0.79	0.36	0.34
E	1.77	1.83	1.87	0.07	0.1	3.6	10.71	1.32	0.32	0.96	0.95
F	2.17	1.41	1.56	-0.75	-0.6	2.32	10.25	0.52	0.20	1.54	1.39
G	1.46	4.34	4.47	2.88	3.01	1.26	2.82	0.28	0.14	0.34	0.33
H	3.63	6.40	6.47	2.77	2.84	3.45	4.82	0.41	0.30	0.57	0.56
I	0.67	0.40	0.40	-0.27	-0.27	9.9	19.31	10.43	0.87	1.70	1.70
J	0.29	0.30	0.30	0.01	0.01	16.76	10.89	17.67	1.48	0.96	0.96
K	0.90	0.35	0.35	-0.54	-0.54		29.28			2.59	2.59
L	15.82	14.97	15.25	-0.85	-0.56	1.62	10.61	0.37	0.14	1.06	1.04
M	0.85	0.99	0.99	0.13	0.13		9.80			0.87	0.87
N[c]	1.53	1.16	1.22	-0.36	-0.3	23.48	10.04	10.45	4.95	1.32	1.25
O	3.45	6.24	6.39	2.78	2.94	1.40	5.38	0.32	0.12	0.55	0.54
P	2.65	1.71	1.71	-0.92	-0.92	114.53	15.93	10.14	10.14	1.54	1.54

[a] Costs are Dynamic EEM plus all Commissioning Costs.

[b] Simple Payback Time: Cx and Dynamic EEM costs; Indirect and Unrelated Cx plus Dyn. EEM savings.

[c] Includes a non-energy benefit discussed in previous subsection, and shown in Figure 5.1.

In general, the cost-benefit ratios were more favorable when the costs and benefits of commissioning and the EEMs are combined, as shown in the final two columns of Table 5.8. Similar to the net savings results, the economic benefits exceed the costs for ten buildings for the low lifetime case, and eleven for the high lifetime case. Average and median cost-benefit ratios are 0.99 and 0.96 for the low lifetime case, and 0.96 and 0.80 for the high lifetime case.

It is interesting to note that there does not appear to be a correlation between the commissioning costs and the cost-effectiveness. The costs for commissioning among the projects that were not cost-effective are scattered among the distribution of costs This can be seen in the scatter shown on Figure 5.2.

Savings by EEM Category

Tables 5.9 through 5.11 present a summary of design predicted energy savings for 45 of the 49 EEMs commissioned for all 16 buildings. Energy savings estimates for commissioning are shown for 21 of the 45 EEMs. In a few cases there are more than one deficiency correction per EEM. There were no quantified deficiency corrections for 24 EEMs, and the value for commissioning savings is blank, or zero. Put more simply, there were deficiency correction energy savings estimates for slightly less than half of the EEMs. The categories are lighting, refrigeration, miscellaneous and four HVAC types: EMCS, economizers, VFDs, and heat pumps. The four measures categorized as miscellaneous were excluded from the tables. For this table, the corrections are all that apply to each dynamic EEM, direct *and* indirect, but not unrelated savings. Thus, the correction savings are often the sum of more than one correction. The averages include zero values for the energy savings, but the ratio averages are only for those ratios that appear. Similar to the tables above, two values for the electricity savings ratios are shown: unadjusted, and adjusted for the difference between the interactive and parametric model results, the latter being generally higher than the former.

Table 5.9 Annual Savings from Commissioning of HVAC EEMs.

Code	Dynamic EEM Savings			Correction Savings			Ratio Corr./EEM			
	Elec. (kWh/ft²)	Gas (kBtu/ft²)	Dem. (W/ft²)	Elec. (kWh/ft²)	Gas (kBtu/ft²)	Dem. (W/ft²)	Elec.	Gas	Dem.	I/P adj Elec.
EMCS										
Energy Management and Control Systems										
D	1.47	25.94	0.12							
E	1.40	2.47	0.08	0.25	-0.22	0.01	0.179	-0.09	0.160	0.150
F	1.24	-1.51		0.73	-0.75	0.07	0.586	0.50		1.244
G	4.48	-5.27	0.90	2.78	0.57	-0.03	0.622	-0.108	-0.040	0.789
H	8.67		3.04	0.21		0.04	0.024		0.012	0.024
L	2.24	1.65								
M	1.16		0.26							
N	0.62	0.03	0.07							
O	2.88	-8.56	0.03	2.34	-3.1	0.00	0.813	0.363	-0.399	0.709
P	2.34		-0.11							
Avg.	2.65	1.47	0.44	0.63	-0.34	0.01	0.445	0.166	-0.066	0.583
Economizers										
B	0.87			0.3			0.350			0.310
I	0.59	0.88	0.08	0.54			0.927			0.806
J	0.22			0.12		0.030	0.554			0.466
O	0.77		0.05	1.11	0.00	0.13	1.449		2.450	1.265
Avg.	0.61	0.22	0.03	0.52	0.00	0.04	0.820		2.450	0.712
Variable Frequency Drives										
D	0.15			0.13		0.10	0.882			0.565
D	0.64		0.06	0.09			0.134			0.086
D	2.01	30.21	0.38							
E	0.09		0.02	0.21			2.271			1.913
E	0.13	0.91	0.02							
E	0.31									
E	1.43	-1.93	0.11	0.05	-0.03	0.02	0.035	0.019	0.214	0.03
F	2.27	-14.92	0.75	-0.02			-0.011			-0.024
G	1.98		0.37							
Avg.	1.00	1.58	0.19	0.05	0.00	0.01	0.662	0.019	0.214	0.514
Heat Pumps										
A	1.32		2.17							
B	0.87		0.18	0.79		0.57	0.905		3.125	0.803
K	0.47		0.06							
M	0.05		0.09							
N	0.08			0.17		0.03	1.962			1.805
N	0.46									
O	0.04		0.03							
P	0.05		0.95							
Avg.	0.46		0.44	0.20		0.08	1.234		2.288	1.112

Table 5.10. Energy Savings from Commissioning of Lighting EEMs.

Code	Dynamic EEM Savings			Correction Savings			Correction/EEM			
	Elec. (kWh/ft^2)	Gas (kBtu/ft^2)	Dem. (W/ft^2)	Elec. (kWh/ft^2)	Gas (kBtu/ft^2)	Dem. (W/ft^2)	Elec.	Gas	Dem.	I/P adj Elec.
A	1.56		0.56	0.04		0.02	0.027		0.027	0.027
E	0.13	-0.01	0.03							
G	0.51		0.14	0.51		0.14	1.00		1.00	1.269
G	0.57									
H	4.19		0.16							
J	0.46	-0.99	0.06							
M	0.26		0.09							
O	0.30	-0.15	0.34							
Avg.	0.54	-0.16	0.17	0.08		0.02	0.514		0.514	0.648

Table 5.11. Energy Savings from Commissioning of Refrigeration EEMs.

Code	Dynamic EEM Savings			Correction Savings			Correction/EEM			
	Elec. (kWh/ft^2)	Gas (kBtu/ft^2)	Dem. (W/ft^2)	Elec. (kWh/ft^2)	Gas (kBtu/ft^2)	Dem. (W/ft^2)	Elec.	Gas	Dem.	I/P adj Elec.
L	25.27	0.21	2.99	4.38		0.54	0.173		0.179	0.168
O	0.26		0.05							
O	0.26	1.48	0.05							
O	0.45	-7.55	0.16							
O	2.50		0.44							
O	3.99	6.73	0.68							
Avg.	5.46	0.14	0.73	0.73		1.07	0.173		2.152	0.168

It is difficult to draw strong conclusions from these data, due to the small sample sizes. With some caveats, we believe the following conclusions are likely to hold true for larger samples. Refrigeration correction savings are both the largest in absolute terms, and the smallest as a percentage of the EEM savings (though this conclusion is drawn from one EEM). Refrigeration EEMs are important to commission because the impact of any failure is likely to be large. Heat pumps have the largest average ratio. That is, when a fault is found with heat pump, fixing it will on average give a larger fraction of the EEM savings than with other categories of EEMs. Notably, problems were found with all four economizers during commissioning. Both EEMs with daylighting controls had commissioning savings.

No obvious pattern emerges regarding gas savings or peak demand savings. There were often increases in gas use, making the ratio or averages of them difficult to interpret. The demand ratios are often greater than one, though this may reflect differences in modeling as much as real effects.

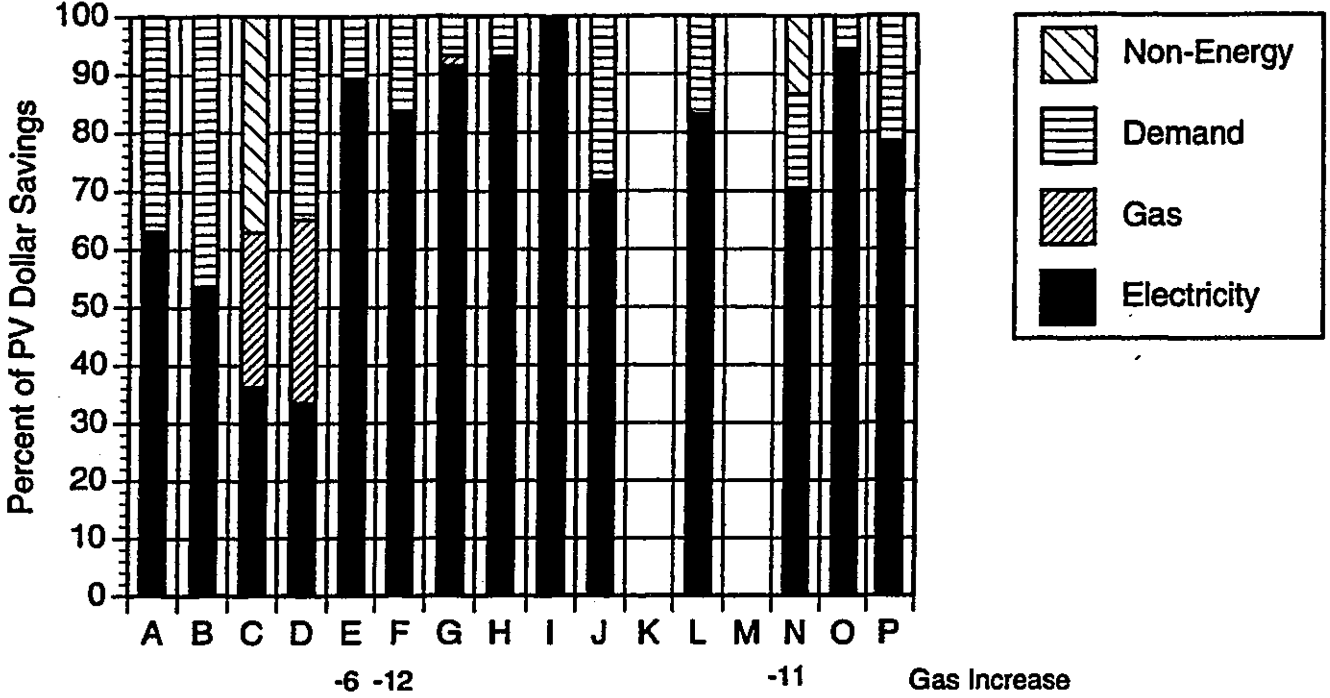

Figure 5.1. Present value of savings from commissioning by energy type, plus sample non-energy benefits estimates. On average, electricity savings accounted for 67% of the total savings. Gas use increased at three sites (Buildings E, F, and N).

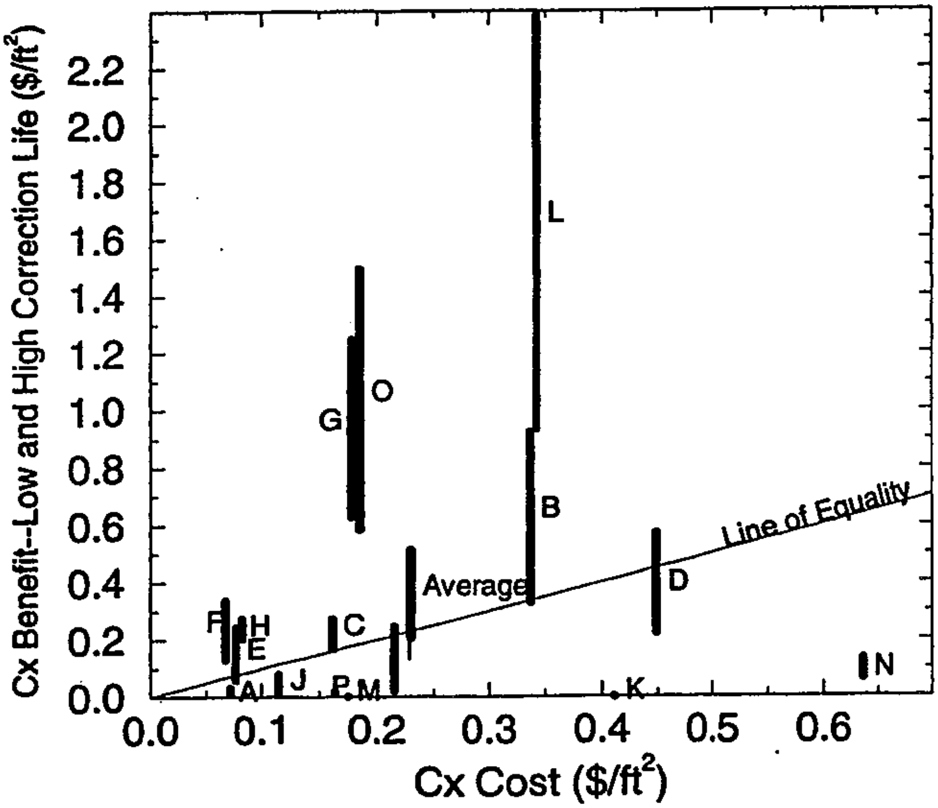

Figure 5.2. Present value of the savings (benefits) from commissioning versus cost of commissioning. The line shows where commissioning costs are equivalent to energy savings benefits.

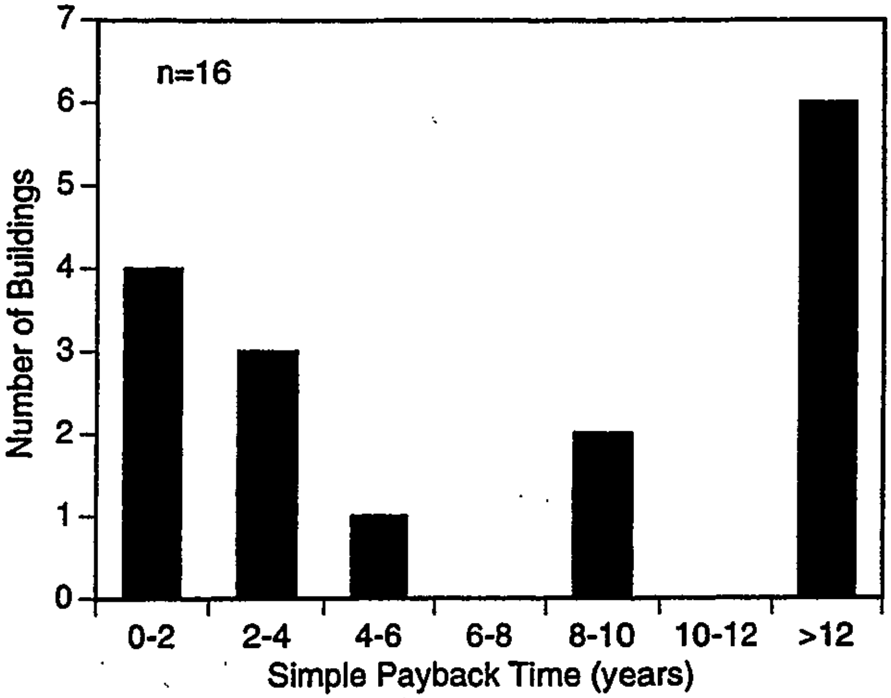

Figure 5.3. Distribution of simple payback times for commissioning as a stand-alone measure.

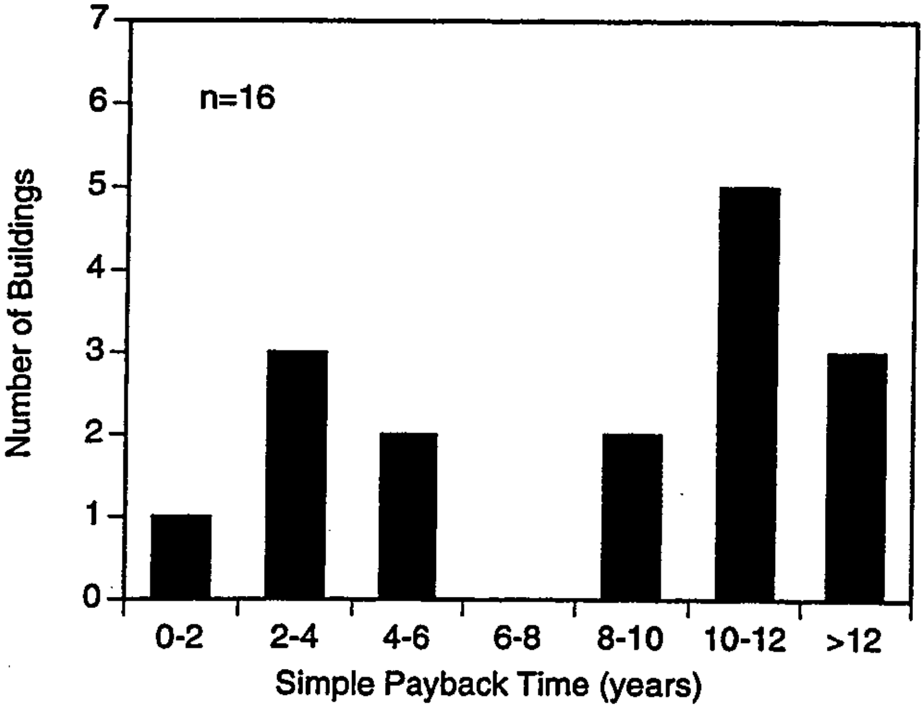

Figure 5.4. Distribution of simple payback times for commissioning combined with the EEMs.

6. Discussion

This section discusses general implications of the findings related to the energy savings and cost effectiveness of commissioning and future directions in utility and related commissioning programs. It has five subsections. The first subsection discusses the results in view of the changing regulatory environment in the utility industry. The second subsection touches on key uncertainties in the findings. The third subsection provides recommendations for future programs. The fourth subsection provides a brief discussion of how commissioning fits in to the broader issue of building performance assurance.

Broadening the Scope and Educating Owners

This study has shown that on average the investment in commissioning was cost effective on energy savings alone. This findings is somewhat uncertain because of the small sample size and lack of metered data in the evaluation. However, it is an important finding that suggests utility sponsored commissioning could be a cost effective component of commercial demand-side management programs. In an era when utilities and energy providers are positioning themselves for a deregulated energy marketplace, companies that offer performance assurance and commissioning are likely to be at an advantage in maintaining customers by understanding and addressing their needs. Such services, applied successfully, should help lower energy bills.

There is a tremendous need to educate building owners about the value of commissioning. Building owners want buildings that work as intended, are comfortable, healthy, and efficient. But building owners are not well informed about the benefits of rigorous functional testing. PacifiCorp found that about half of the building owners involved in the program felt that commissioning was valuable, while about half felt it was a burden in the construction and financing schedule. Full payment for EEMs was not available until severe deficiences were corrected. Building owners need to be educated about both the energy and non-energy benefits of commissioning.

Building owners (and operators!) also need to be educated about the performance of individual EEMs relative to whole-building systems. While commissioning within FinAnswer and most other utility programs is targeted at individual EEMs, the distinction between EEM and whole-building commissioning is blurred by the integrated nature of building systems. This is especially true with larger, more sophisticated buildings. Future commissioning programs may explore methods to target commissioning of the most important energy using systems rather than individual EEMs. Looking again at whole-building performance, it is important to recognize that the performance of static EEMs can also be improved with performance tests. Duct leaks, window-frame leaks, and structural infiltration cause significant increases in energy use.

There were deficiences that were not corrected at nearly every building. This finding suggests that the technical potential for energy savings from commissioning and subsequent attention to O&M are greater than the savings captured by the commissioning discussed above. There are diminishing returns, however, in chasing down minor problems, although not all of the outstanding problems were minor. It is ultimately up to the building owner to follow-up on correcting outstanding deficiences. Building owners may be reluctant to invest in fixing problems in a new building, and certainly frustrated to hear of their existence in the first place.

Uncertainties and Research Needs

There are a variety of uncertainties in the findings from this study. It is useful to discuss them with an eye toward improving future evaluation efforts and developing a better understanding of the costs and benefits of commissioning and related operations and maintenance programs and processes. The key uncertainties in this study can be categorized into four issues: (1) uncertainty in the lifetime of a deficiency correction, (2) difficulty evaluating energy savings benefits, (3) difficulty evaluating non-energy benefits, (4) small sample size and associated statistical uncertainty. Each of these suggest the need for further research, which we comment on in general terms.

Uncertainty of Correction Lifetime.

Starting with the first issues, as discussed in Section 3, we assumed that all deficiences would have gone undetected without commissioning. We can only estimate the lifetime of the corrections, which are often linked to ongoing O&M practices. The commissioning procedures within Energy FinAnswer have helped improve O&M. CA's often reported that it required substantial effort to compile appropriate documentation and specifications on various building equipment for the O&M manual. Anecdotal evidence from CAs and the Technical Coordinator suggest that upon visiting the buildings several months after commissioning some systems had fallen into a state of disrepair. This is especially common with economizers. Better information on ongoing O&M practices is needed to understand how commissioning improves the equipment over its full useful life, and when additional intervention may be needed. For large buildings, examination of O&M logs combined with EMCS trend logs and submetered energy use data might help reveal useful information about the relationship between energy use and O&M.

Uncertainty of Energy Savings.

Computer simulations allow us to track complex interactions among building systems. One complication in estimating the energy impact of a change in a building system is that buildings typically differ greatly from their design models. Another difficulty is that simulations are often limited in their ability to characterize improper building operations. There were five specific problems we confronted in using the design models for the energy savings estimates. These are discussed below.

- *Errors in design model or simplistic use of DOE-2 —*
  We found several problems in the original design models. This findings suggests there is a need for better review of the models during the design stage.
- *Differences between the actual building and the design model —*
  We accounted for these changes on a limited basis. For example, we made several changes to the model of the night purge at Building E to better reflect the actual control logic used in the EMCS. This is similar to "tuning" a design model to "as-built" or "as-operated" conditions. But, as mentioned, we did not tune the models with measured data, because the data were not available. This finding suggests the need to link assumptions in models to documenting as-built and as-operated conditions found during commissioning. Such information would help streamline the evaluation process.
- *Simulation program unable to model certain features —*
  DOE-2 is unable to model certain building systems in a rigorous manner. For example, DOE-2 can't reset duct static pressure as is done at Buildings E and H. Such shortcomings of DOE-2 should be stated clearly when modelers conduct their

preliminary design work for Energy FinAnswer, and they usually are not.

- *Differences between parametric and interactive runs —*
  As discussed in Section 5, this can be a large effect for some measures and buildings. It highlights the need to look at complete building systems as opposed to individual components.
- *Errors and inconsistencies in modeling summaries —*
  For example, at Building F the EEM summary tables neglected to include the gas increase that resulted with one EEM (the use of VAV with the VFDs). We found discrepancies between the "combined" measure and the sum of the individual ones listed in some of the summary tables.

One general conclusion that would help address all of these uncertainties is to increase the use of metered data in evaluating the benefits of commissioning. An important issue that is beyond the scope of this study is the subject of how commissioning influences whole-building perfomance. We have not linked these savings estimates to the total energy use. This was not done because monthly utility billing data were limited since the buildings are new. Utility bills were collected for the first few buildings. They were not useful because only a few months of data were available at most of the sites.

It would be useful to compare the total energy use to design predicted energy use as building operations become more stable and the buildings are more fully occupied. In the Energy Edge project we found that energy-use would slowly rise over the first few start-up years in a new building (Piette et al., 1994).

Uncertainty of Non-Energy Benefits.

The third category of uncertainty is related to the non-energy benefits that are not generally considered in our economic analysis. There are opportunities to improve the quantification of non-energy benefits, but such an effort was beyond the scope of this study. These benefits could be quantified by examining operating costs in commercial buildings, and exploring how commissioning might influence them. For example, many of the deficiency corrections involved reducing the rapid cycling of compressors. To quantify the benefit of this correction one would examine equipment lifetimes and degradation factors to try to assess the overall impact of rapid cycling. Another example would be to examine the range in indoor temperatures and other data from EMCS of in commissioned buildings to try to evaluate how the deficiency corrections improve comfort conditions. Building operators would likely spend less time addressing hot and cold calls, occupants would spend less time complaining, and may be more productive. Building owners would likely be convinced that commissioning is valuable if the link to comfort could be more carefully established.

Uncertainty from Small Sample Size.

The final uncertainty in the results of this particular study is the small sample size. The 16 buildings appear to be typical of the others within the FinAnswer program. This uncertainty could be reduced by conducting similar analysis with additional buildings. Future evaluation efforts would benefit from developing more structured problem descriptions.

Recommendations for Utility Funded Commissioning

Several recent papers have discussed recommendations for cost-trimming within utility commissioning programs (Kaplan, 1994, Stum and Haasl, 1994, and PECI, 1994). We summarize some of the key points from these papers, and add a few others.

First, it is important to communicate clearly with CAs about their responsibilities, use only those who are consistently reliable, and support them with training. Standardized test plans are needed that put the greatest commissioning effort into energy intensive systems. EMCS trending should be used in performance tests when possible. EEM specifications should be detailed to ensure that installers understand them.

The evaluation of savings from commissioning provides useful feedback results to program-wide savings estimates. This evaluation should include obtaining direct feedback from CA on benefits of commissioning. The CA was often the best source of information on the implications of a deficiency. It may be useful to use a questionnaire to obtain such information. The CA was not, however, particularly helpful in quantifying energy savings benefits.

Ultimately it would be useful to provide feedback to building designers on problems encountered during commissioning. Such process oriented questions, while beyond the scope of this study, are of general interest because of the broad nature of the problem. Commissioning agents develop first hand experience with installed building systems and often have strong opinions about the quality of the design.

On the other end of the building life cycle it is useful to enhance the relationship between information gained during commissioning and ongoing O&M. Perhaps the greatest uncertainty about the value of commissioning is the question of persistence of savings. Attention to EEM performance must continue after the acceptance phase. Annual or bi-annual tune-ups may prove to be cost effective once a building is properly commissioned. These tune-ups might include some of the same tests as those conducted during commissioning to evaluate whether the same problems have returned.

The Future of Commissioning: Life-cycle Performance Assurance

The broad goal of this study and others similar to it is to examine the costs and benefits of commissioning in order to increase the understanding of the value of such processes. As knowledge about the concept and processes of commissioning becomes more widespread there are opportunities to move functional and diagnostics tests into more common practice. Several possible deployment options are being explored, such as building codes, utility rebates, and design assistance. The Energy FinAnswer program has demonstrated a successful approach to training commissioning agents and improving building performance. The entire Pacific Northwest, and perhaps the entire nation, has benefited from PacifiCorp's leadership.

Another facet to evaluating the future of commissioning is the consideration of eliminating the need for it in the first place. Who should be responsible for performance checking? Standardization in testing could help ensure that controls contractors deliver fully functional system. Commissioning is often considered an element of total quality management (TQM). Following the principles of TQM, commissioning establishes important metrics that can be used to judge efficiency and building performance throughout the life of a building. One of the barriers in achieving further savings is the lack of data analysis techniques that allow the owner or building operator to understand the value of making a control or equipment change.

Ideally, these activities would include a combination of spot, short-term and long-term monitoring, combined with ongoing EMCS monitoring, to verify proper installation and operation of building systems. The use of monitored data will improve our ability to quantify benefits from commissioning. Efforts are underway in related research to enhance the data monitoring and diagnostic capabilities of future EMCS for use in the commissioning process (Heinemeier and Akbari, 1992). Too often, today's EMCS are underutilized and overly complicated.

An even broader vision of the future of commissioning suggests a need for more integration of building performance data over the building lifetime. Performance design specifications could be tracked from computer aided design drawings through construction, and updated with as-built systems. One common finding in the commissioning reports was that design intentions, especially control sequences, were often not well defined. Almost half of the deficiency corrections involved correcting control settings and software programming. Documentation from commissioning agents should be added electronically to historic building files, perhaps using the EMCS as the main platform for performance diagnostics and real-time simulation.

7. References

ASHRAE, *ASHRAE Guideline 1-1989, Commissioning of HVAC Systems.* Atlanta; American Society for Heating, Refrigeration, and Air-Conditioning, 1989.

Benner, N. and Bjomskov, D. "Building Commissioning: Reliability, Persistence and Change," *Proceedings of the Second National Conference on Building Commissioning,* St. Petersburg, Florida, May 9-11, 1994. Proceedings published by PECI, Portland, Oregon.

Claridge, D., Haberl, J., Liu, M., Houcek, J., and Athar, A., "Can You Achieve 150% of Predicted Retrofit Savings? Is it Time for Recommissioning" *Proceedings from the ACEEE 1994 Summer Study on Energy Efficiency in Buildings,* Vol. 5, American Council for an Energy-Efficient Economy, Washington D.C., August 1994.

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

Kaplan, M., "Cost Trimming in a Utility Program," *Proceedings of the Second National Conference on Building Commissioning,* St. Petersburg, Florida, May 9-11, 1994. Proceedings published by PECI, Portland, Oregon.

Kaplan, M., personal communication, January 3, 1995.

Portland Energy Conservation, Inc. (PECI), "Summary Report" *Proceedings of the Second National Conference on Building Commissioning,* St. Petersburg, Florida, May 9-11, 1994. Proceedings published by PECI, Portland, Oregon.

Piette, M.A., Diamond, R., Nordman B., de Buen O., Harris J.P., Heinemeier, K., and Janda, K. *Final Report on the Energy Edge Impact Evaluation of 28 New, Low-Energy Commercial Buildings,* Report to the Bonneville Power Administration, LBL-33708, February 1994.

Sterling, E. and Collett, C., "The Building Commissioning Quality Assurance Process in North America," *ASHRAE Journal,* Vol. 36, Number 10, October 1994.

Stum, K. and Haasl, T., "Costs and Savings of ECM Commissioning and Inspection; Case Studies from One Utility," *Proceedings of the Second National Conference on Building Commissioning,* St. Petersburg, Florida, May 9-11, 1994. Proceedings published by PECI, Portland, Oregon.

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, American Council for an Energy-Efficient Economy, Washington D.C., August 1992.

Yoder, R. "What Does It Cost to Commissioning a Building, Data from Three Year's of Energy FinAnswer Projects" *Proceedings of the Second National Conference on Building Commissioning,* St. Petersburg, Florida, May 9-11, 1994. Proceedings published by PECI, Portland, Oregon.