Public Interest Energy Research on Building Commissioning in California

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ABSTRACT

An estimate of as much as 30 percent of all energy that is consumed by commercial buildings in the U.S. is due to inefficient and improper operation of building equipment. A lack of or inadequate building commissioning and diagnostic efforts, inadequate maintenance, outdated and inefficient equipment are some of the more common sources of problems in non-residential buildings. Many of these problems are often ignored or left unresolved because building staff and operators lack the critical information necessary to address them. Three building commissioning research projects funded under the Public Interest Energy Research (PIER) program investigate the energy saving potentials through proper use of sensors, data storage frequency for HVAC fault detection and diagnostics to optimize commercial building systems to perform at their peak energy efficiency.

The goal of these projects are to improve the cost-effectiveness of sensor accuracy and data storage frequency, building fault detection and diagnostics (FDD), commissioning, and measurement and verification (M&V) techniques through the further development of existing tools and techniques in these four areas. The results of these projects show that these commissioning tools are very promising and cost effective in each application. Other benefits observed include extending equipment life and reducing equipment failures and improved occupant comfort and indoor air quality leading to reduced tenant complaint.

Background

Before the restructuring of California's electricity industry in 1996, retepayer-funded energy-related research, development and demonstration projects were primarily conducted by the State's regulated utilities. Energy-related public interest research and development was a key component of the rate structure mandated by the California Public Utilities Commission for the investor-owned utilities. During this period, California led the nation in developing and deploying a wide range of innovative energy technologies and services that were environmentally sound and saved retepayers billions of dollars through improved generation and /or end-use efficiencies.

In 1996, California significantly restructured the electricity services industry in this state through the enactment of Assembly Bill (AB) 1890. In AB 1890 the

Legislature expressly determined that those research development and demonstration (RD&D) activities which serve a broader public interest " should not be lost in the transition to a more competitive environment." To ensure continued funding for energy-related public interest RD&D, the Legislature authorized the collection of at least $62.5 million annually to provide for these "public goods" efforts. One of the six Public Interest Energy Research (PIER) research program areas established was the buildings efficiency program.

Introduction

Commercial buildings in California consume approximately 70% of the 642 trillion Btu total energy used in the commercial sector in the form of natural gas and electricity (Energy Efficiency Report, CEC,1993). An estimate of as much as 30 percent of all energy that is consumed by commercial buildings in the U.S. is due to inefficient and improper operation of building equipment (Katipaluma, 1999). A lack of or inadequate building commissioning and diagnostic efforts, inadequate maintenance, outdated and inefficient equipment are some of the more common sources of problems in non-residential buildings. Many of these problems are often ignored or left unresolved because building staff and operators lack the critical information necessary to address them.

Three building commissioning and diagnostic research projects were funded out of the PIER transition funding phase for a total of $900,000. These projects were conducted to investigate the energy saving potentials through proper use of sensors, data storage frequency for HVAC fault detection and diagnostics to optimize commercial building systems to perform at their peak energy efficiency. The goals of the initial stage of building commissioning research are to conduct energy performance monitoring in a cost-effective way and to provide the building operators a way to improve the HVAC system performance. It is also of vital importance to find a way to encourage building owners to design and operate their buildings in the most efficient way.

To accomplish these goals, work was broken down into a number of research projects. The California Energy Commission (CEC), through its Public Interest Energy Research (PIER) Program, sponsored the following projects:

Project Title	**Research Scope**	**Goal of Research Effort**
1. Improving the Cost-Effectiveness of Building Control Systems Sensing and Data Collection	Sensor accuracy and data collection frequency for building commissioning.	To develop a method to determine cost-effective measurement accuracy and data storage frequency recommendations for energy management control systems.

2. Improving the Cost-Effectiveness of Building Diagnostics, Measurement and Commissioning Using New Techniques	New techniques for building performance measurement, verification and analysis.	To investigate and demonstrate tools to reduce the cost of measurement and verification, building commissioning and diagnostic services including a BACnet access link.
3. Diagnostics for Building Commissioning and Operation	Evaluation of a state-of-the-art building energy information technology demonstration project	To demonstrate an Information Monitoring and Diagnostic System (IMDS) that allows building operations staff to monitor and visualize the energy use and diagnose HVAC problems.

Research Approach and Findings

The research reports for these projects are being finalized at this time. Due to the limited space allowed for this paper, detailed assumptions and methodologies can not presented. The following is a summary of the approach and findings for each project:

Measurement Accuracy and Data Storage Frequency Project

First, the contractor prioritized building plant systems/equipment to be evaluated. Then a survey and interviews with building operators were conducted to determine how they currently use their energy management control systems. Based on the survey and the results of the interview, the contractor prioritized which systems and evaluations were most important to the building operators. Air handling units and chillers/cooling towers were the top two selections for sensor accuracy and data storage evaluation. Lighting, boiler, pumps, terminal units, thermal storage and plug loads did not make the list due to their low scores. Because of limited research funding, the study was focused on air handling units.

The method to determine accuracy was developed from common economic analysis techniques, where the benefits of an improvement are compared to the costs. The benefits are determined from the sensitivity of the building's energy use to the improvement in measurement accuracy. The costs cover installation of more accurate sensors and annual calibrations to maintain accuracy. Greater accuracies are justified when the benefits are greater than the costs of the improvements. Data storage frequencies are based on 1) enabling detection of system dynamics such as control instabilities and scheduling problems and 2) the number of readings needed to minimize the uncertainty of performance test results.

The method involves first determining the measurements, factors, algorithms, or plots required for the types of evaluations to be performed with the equipment. Next, site data is collected to produce sample plots and calculate performance factors. For parameters that affect energy efficiency, sensitivity analyses are performed to determine their effect on building energy. Using a bin energy analysis model of a 50,000-square-foot office building in Alameda and Sacramento, we calculated how much the building energy use changes with small changes in the input parameters (from their base case values). The parameters that we varied were those that affect fan and chiller energy use, or that can be used for diagnostics. Finally, we verified the results and expanded the analysis to other buildings (50, 250, and 1,000 thousand square-foot office buildings and a 250 thousand square-foot hospital) in similar climate zones (San Francisco and Fresno) using DOE-2 model simulations. The economic benefit of a measurement's accuracy is compared to the assumed cost of installing and maintaining accurate instrumentation, to determine the level of instrument accuracy required to produce energy savings.

To verify the method's general usefulness, we also applied it to measurements used for several commissioning scenarios related to the use of air-handling equipment. Table 1 shows the recommended accuracies and storage frequencies, as well as the economic commissioning scenarios, from our verification analyses. Table 2 shows the maximum potential savings that could result, if the recommendations for accuracy and commissioning are adopted. In summary, the supply air and chilled water temperatures should be 0.5°F accurate for all of the sites. Duct static pressure and air filter differential pressure should be 0.2inH_2O accurate for all of the sites. Zone temperatures need only be better than 2°F accurate for the hospital buildings (0.5°F), because of their 24 hour operating periods and large amount of energy use for zone reheat control. Outside and return air temperature accuracies should be 0.5°F accurate, except for the small and medium office buildings in Fresno, which require only 2°F accuracy, since they operate for fewer hours around the economizer change point.

Commissioning activities were justified for only the buildings with a large amount of energy use. Of the scenarios that we considered, the most economically attractive activities were 1) monitor coil differential pressure, 2) monitor outside air flow, and 3) verify fan performance. Note that only a few commissioning activities were considered here (those related to sensor accuracy); those required for comfort and safety were not analyzed. The totals for maximum potential savings ranged from $1,756 to $184,520 per year for the eight buildings considered. The greater the building's energy use, the greater the potential for savings. The ratio of savings to total energy costs ranged from 2 to 12%. The greater the building's energy use, the greater the accuracy requirements and the more commissioning activities that can be justified.

Table 1. Summary of Recommended Sensor Accuracies for All DOE-2 Example Sites

Air Handler Operation and Control - Sensors	Fresno Small Office	Fresno Medium Office	Fresno Large Office	Fresno Medium Hospital	S.F. Small Office	S.F. Medium Office	S.F. Large Office	S.F. Medium Hospital	Recommended Storage Frequency (from Diagnostic Plots)
Supply Air Temperature	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	2 min
Single Zone Temp (1000 sf)	2°F	2°F	2°F	0.5°F	2°F	2°F	2°F	0.5°F	2 min
Duct Static Pressure	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	1 min
Filter Differential Pressure	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	Every 3 months
Outside Air Temperature	1°F	1°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	5 min
Return Air Temperature	2°F	2°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	1 min
Chilled Water Temperature	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	2 min
Commissioning Activity, Improvement, or Sensor Installation									
Calibrate Zone Min Air Flow at Zero	-	-	-	-	-	-	-	-	N/A
Install New Zone Air Flow Sensor	-	-	-	-	-	-	-	-	N/A
Monitor Coil Differential Pressure	-	-	0.05 inH_2O	0.05 inH_2O	-	-	0.05 inH_2O	0.05 inH_2O	Every 3 months.
Install an Outside Air Flow Sensor	-	5% of min flow	5% of min flow	-	-	-	5% of min flow	-	Every 5 minutes
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	-	-	-	-	-	-	-	-	N/A
Test Coil Performance	-	-	5% Eff.	-	-	-	-	-	Test every few year
Test Fan Efficiency	-	-	5% Eff.	5% Eff.	-	-	-	5% Eff.	Initial Test Only

Table 2. Summary of Potential Savings for All DOE-2 Example Sites

Air Handler Operation and Control - Sensors	Fresno Small Office	Fresno Medium Office	Fresno Large Office	Fresno Medium Hospital	S.F. Small Office	S.F. Medium Office	S.F. Large Office	S.F. Medium Hospital
Supply Air Temperature	$297	$1,740	$8,992	$48,459	$164	$1,097	$3,264	$27,666
Single Zone Temp (1000 sf)	-	-	-	$49,641	-	-	-	$30,744
Duct Static Pressure	$513	$3,243	$15,387	$26,944	$282	$2,130	$10,938	$21,113
Filter Differential Pressure	$513	$3,243	$15,387	$26,944	$282	$2,130	$10,938	$21,113
Outside Air Temperature	-	-	$175	$2,050	$544	$2,736	$16,474	$651
Return Air Temperature	-	-	$175	$2,050	$544	$2,736	$16,474	$651
Chilled Water Temperature	$434	$2,660	$10,243	$8,048	$104	$783	$6,956	$3,698
Commissioning Task, Improvement, or Sensor Installation								
Calibrate Zone Min Air Flow at Zero	-	-	-	-	-	-	-	-
Install New Zone Air Flow Sensor	-	-	-	-	-	-	-	-
Monitor Coil Differential Pressure	-	-	$2,180	$3,945	-	-	$1,397	$2,655
Install an Outside Air Flow Sensor	-	$2,548	$15,501	-	-	-	$6,591	-
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	-	-	-	-	-	-	-	-
Test Coil Performance	-	-	$11,973	-	-	-	-	-
Test Fan Efficiency	-	-	$6,315	$16,441	-	-	-	$10,981
Total Potential Annual Savings	$1,756	$13,433	$86,327	$184,520	$1,919	$11,612	$73,031	$119,272
Total Building Energy Use (MWh/yr)	752	3,546	14,820	11,207	620	2,941	11,829	8,785
Total Building Energy Cost (k$/yr)	$94k	$439k	$1,872k	$1,597k	$77k	$364k	$1,497k	$1,215k
% Savings vs. Total Energy Cost	1.9 %	3.1 %	4.6 %	11.6 %	2.5 %	3.2 %	4.9 %	9.8 %

Note: The Total Potential Annual Savings includes all improvements listed. In reality, most sites would require only a subset of th them.

Commissioning and M&V Tools and BACnet link Development Project

A literature search in technical journals, trade publications, and web sites, as well as surveys of researchers, building operators, tool developers, and other interested groups, was performed to assess of the current state of building fault detection and diagnostics (FDD), commissioning, and measurement and verification (M&V) tools. The final tool selections were made by following a five-step methodology.

1. Assess the Current State of Research and Scan Diagnostic, Measurement and Commissioning Technologies. Develop a clear picture of the need for and availability of present tools and techniques for diagnostics, commissioning and Measurement and Verification (M&V).
2. Define the Research Priorities. Analyze various aspects of diagnostic, M&V, and commissioning tools or techniques and prioritize them on the basis of their impact and cost benefit.
3. Design a Research Plan for Development of Select Tools or Techniques. Develop an integrated research plan for substantial development and testing of up to six candidate tools or techniques in order to maximize the impact and value of the tools or techniques developed under the limits of the project budget.
4. Engineering Development, Test and Evaluation of Procedures and Technologies. The research plans for the selected tools would be carried out through engineering development and bench testing.
5. Complete Testing and Evaluate Candidate Techniques and Technologies. The testing and evaluation carried out in this step would show how well these tools work in the field and provide the data to support the final report and technical papers written as a result of this work.

As a result of the above methodology, six technologies were identified as candidates for further development and testing on the basis of their possible impacts and cost benefits to the California commercial building industry. Due to the project's budget and time limits, only four of these six technologies were selected for further development and testing. The four technologies selected were:

1. Model-independent fault detection and diagnostics for variable-air-volume (VAV) terminal units. This tool is based on a residual approach rather than the traditional model-based approach for fault detection and diagnostics (FDD) preprocessors. The approach used is "model-independent" because it does not require that the tool be calibrated, or "trained," for each individual system using large amounts of historical data. By avoiding model-based approaches, implementation of this tool in real-building environments should be expedited and less capital intensive.
2. First principles model for integrated cooling systems. This tool focuses on identifying the minimum amount of historical data needed to accurately predict cooling system performance in a typical commercial building. This tool addresses the need for more generic, less cumbersome modeling techniques.

3. BACnet™-based Building Control System Driver to Facilitate FDD in Open Architecture EMCS. This tool is a communications interface for controls systems employing native BACnet™ or BACnet™ gateway open protocols. Such an interface allows client applications access to data collected by the energy management control system (EMCS), without taxing its computational resources. This provides a generic hardware and software platform for performing FDD or even M&V activities through existing building EMCSs.
4. M&V Value Tool. The M&V Value tool is a database-driven program that allows the user to evaluate different M&V scenarios to determine appropriate M&V costs and savings uncertainty for specific energy-efficient measures. An M&V plan's cost-effectiveness, together with consideration of a project's tolerable risk, are the major elements in selecting the best M&V plan for a project. This tool will be useful for utilities, M&V practitioners, and energy service companies.

Results of Tool Development

Tool #1 The Model-Independent Fault Detection and Diagnostics (MIFDD) tool was developed for pressure-independent VAV terminal units. Simulation and laboratory testing of MIFDD successfully demonstrated its ability to detect and diagnose nearly 40 different failure modes for pressure-independent VAV terminal units using only design and measured parameters. Easy implementation of the tool in real building environments will address situations in which failures directly affecting occupant comfort are common but preventative maintenance programs are rarely successful due to the large number of individual units in a building.

Tool #2 A steady-state, physical-based modeling tool for predicting operation of chilled water, variable-air-volume building HVAC systems using a minimal amount of training data has been successfully developed and tested. Using a minimal data set consisting of three days of laboratory testing, the model was successfully calibrated and able to accurately predict the operation of the laboratory system evaluated.

Tool #3 The BAClink driver was developed to help access building system information necessary for implementing FDD and M&V methods in conjunction with BACnet™-based building controls systems. Design specifications for a BAClink driver to interface with Pacific Gas & Electric Company's Pricing Control Software (PCS) have been developed. Prior to performing in-situ testing of the driver, bench testing was performed.

Tool #4 The M&V Value tool is a program that allows the user to evaluate different M&V scenarios to determine M&V costs and savings uncertainty. The M&V Value Tool is a database application that estimates the total uncertainty of an energy savings estimate for a specific end use. This testing confirmed that the as-designed tool relied on realistic data in order to be useful, and indicated where a significant improvement in the tool was warranted. This improvement was an equipment table user interface form to add measurement device information, enabling users to customize the tool to their own situation. The tool was also checked against actual data from lighting and motor efficiency improvement projects. The investigated scenarios showed that the overall uncertainties and costs were reasonable, although there was no uncertainty and cost data against which these results could be compared. This test did reveal several areas in which the tool could be improved such as improving the M&V cost model and expanding the number of M&V methods for lighting and motor projects.

IMDS Demonstration Project

The IMDS has successfully operated from 1998 to July 1999 with a small amount of data loss during the first few months of commissioning and has been well received by the building's Technical Manager and Chief Engineer. These building operators value being able to continuously archive key building performance data for analysis using higher quality graphics than those typically available. They recommend that similar technology should be adopted in other buildings. They also recommend that the data be available remotely using the Internet and web-based data visualization tools.

The IMDS has shown the building operations staff a series of critical control problems that they did not know existed. They believe they would find similar problems in other buildings. We have not achieved the 15% energy savings from building tune-up activities that are often possible with such technology; however, the IMDS has been used to solve control problems and improve overall comfort. The automation of the controls has been improved greatly, freeing up time for the staff to take care of other tenant needs. The air distribution system in the building has been balanced, potentially improving health, comfort, and productivity. The reduction in labor-hours required to operate the building as a result of the IMDS is worth about $20,000/year. These savings would pay for the IMDS in about five years. The operations staff expects to see even greater savings as they proceed with a control retrofit planned using the IMDS. The research team presented the operations staff with a series of recommendations for actions to achieve additional energy savings, some of which will be adopted over the next year. The operations staff estimates they could reduce steam use by 50% with recommended retrofits implemented.

Conclusions

Overall, the research results are encouraging. Direct economic benefits to California as a result of the development and use of the techniques investigated under these projects could be significant. Based on the current stage of development to improve the cost-effectiveness of building commissioning and diagnostics, the following conclusions can be drawn for each project.

Measurement Accuracy and Data Storage Frequency Project

A method was developed which can be used to determine accuracies and storage frequencies needed for various data acquisition functions in commercial HVAC systems. The goal is to decrease building operating costs and energy usage by selecting the most cost-effective level of EMCS sensor accuracy and useful level of storage frequency. The method was applied to models of buildings of various sizes and types, in two extreme weather climates in California. Recommended accuracies and storage frequencies are shown in Table 1 above. As expected, the buildings with greater energy use can justify better accuracies and more commissioning activities. Table 3 summarizes the total potential annual savings that could be achieved, if all of the recommendations are followed at the example sites. Potential savings range from 2 to 12 percent of the sites' total energy costs.

Table 3. Summary of Maximum Potential Savings for All DOE-2 Example Sites

Totals	Fresno Small Office	Fresno Medium Office	Fresno Large Office	Fresno Medium Hospital	S.F. Small Office	S.F. Medium Office	S.F. Large Office	S.F. Medium Hospital
Total Building Energy Use (MWh/yr)	752	3,546	14,820	11,207	620	2,941	11,829	8,785
Total Building Energy Cost (k$/yr)	$94k	$439k	$1,872k	$1,597k	$77k	$364k	$1,497k	$1,215k
Total Potential Annual Savings	$1,756	$13,433	$86,327	$184,520	$1,919	$11,612	$73,031	$119,272
% Savings vs. Total Energy Cost	1.9 %	3.1 %	4.6 %	11.6 %	2.5 %	3.2 %	4.9 %	9.8 %

Commissioning and M&V Tools and BACnet Link Project

Development objectives for each of the selected four technologies were achieved during this project. Tool 1 was successfully developed and tested, providing fault detection and diagnostic capabilities for nearly 40 different failure modes for VAV terminal units. For tool 2, the minimum historical data sets necessary to accurately calibrate and model the performance of chilled water systems were identified and successfully demonstrated in a laboratory environment. Tool 3 was developed and the concept of simplifying the collection of measured building operational parameters was successfully demonstrated at a BACnet™ compatible office building. Finally, tool 4 has been developed and the potential for use as a planning and development tool demonstrated for common energy efficiency improvement measures.

IMDS Demonstration Project

Overall the IMDS has been successfully deployed and maintained during the project. While we have not met the 15% savings objective, we have identified more than 15% in energy savings that are possible if the controls were properly functioning. The operations staff expects to see even greater savings as they proceed with a control retrofit planned using the IMDS. The research team presented the operations staff with a series of recommendations for actions to achieve additional energy savings, some of which will be adopted over the next year. The model-based chiller fault detection work is underway. This will help building operators identify and diagnose important control problems. Additional demonstration sites in different climate zones will help. The information of this project is available on the web at http://poet.lbl.gov/tour/. Detailed chiller modeling and technology innovation theory research information will be presented in separate ACEEE papers.

While the information gathered from these research projects is useful, continued research and demonstration will be needed to bring them to the commercial market. The State of California sponsored PIER program will continue to support this effort. PG&E will co-sponsor a high performance commercial building systems research program with

CEC. LBNL will lead a team of experts to evaluate the life-cycle tools and the integrated commissioning and diagnostics. Participating organizations include Massachusetts Institute of Technology, Texas A&M University, PECI, Honeywell Corporation, U. C. Berkeley and other research organizations. Together, these institutions have coordinated their scopes of work to create an integrated building commissioning research that will accelerate the market transformation effort. In addition, part of the information and commissioning tools may be used in the future Title 24 (the building standards in California) development. This will also enhance the CEC's effort to implement the energy saving practices in commercial buildings.

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