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REVIEW OF METHODS FOR MEASURING AND VERIFYING SAVINGS FROM ENERGY CONSERVATION RETROFITS TO EXISTING BUILDINGS

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ABSTRACT:

The Measurement & Verification (M&V) process has evolved in the last 15 years to provide a high confidence approach for determining the resulting savings from a variety of retrofits and energy efficiency enhancements. M&V has a dual role. First, it quantifies the savings being obtained. Since the persistence of savings has been shown to decrease with time,[1] long-term M&V provides data to make these savings sustainable. Second, M&V must be cost effective so that the cost of measurement and the analysis does not consume the savings.[2,3] Currently, a goal of about 5% of the savings per year has evolved as a preferred criteria for costing M&V, since the cost justification directly results from the savings obtained. The general procedure involves a selection of using a monthly billing analysis, a daily or hourly procedure, a component isolation analysis, or a calibrated simulation. Calibrated simulations are usually expensive and difficult to complete.

In summary, this paper covers a brief history of M&V in the United States, an overview of M&V Methods, a cost benefit analysis, and cost-reduction and M&V sampling strategies.

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[1] Claridge D.E., Turner, W.D., Liu, M., Deng, S., Wei, G., Culp, C., Chen, H., Cho, S. 2002. “Is Commissioning Once Enough?” Solutions for Energy Security and Facility Management Challenges: Proceedings of the 25th WEEC, Atlanta, GA, October 19-11, 2002, pp. 29–36.

[2] Haberl, J., Lynn, B., Underwood, D., Reasoner, J., Rury, K. 2003. “Development an M&V Plan and Baseline for the Ft. Hood ESPC Project,” ASHRAE Seminar Presentation, (June).

[3] Culp, C., Hart, K.Q., Turner, B., Berry-Lewis, S. 2003. “Energy Consumption Baseline: Fairchild AFB’s Major Boiler Retrofit,” ASHRAE Seminar (January).

TABLE OF CONTENTS

1 Introduction

1.1 Measurement & Verification Method Selection

Measurement & Verifications (M&V) has a dual role. First, M&V quantifies the savings being obtained. This applies to the initial savings and the long-term savings. Since the persistence of savings has been shown to decrease with time,[4] long-term M&V provides data to make these savings sustainable. Second, M&V must be [1]cost effective so that the cost of measurement and the analysis does not consume the savings.[5,6] The 1997 International Performance Measurement and Verification Protocol (IPMVP) set the target costs for M&V to be in the range of 1% to 10%, depending upon the Option selected, of the construction cost for the life of the ECM. Most approaches fall in the recommended range of 3% to 10% of the construction cost. The IPVMP 2001 removed this guidance on the recommended costs for M&V. Currently, a goal of about 5% of the savings per year has evolved as a preferred criteria for costing M&V, since the cost justification directly results from the calculation.

A general procedure for selecting an approach can be summarized by the following five steps:

a) *In general one wants to try to...*Perform Monthly Utility Bill Before/After Analysis.
b) *And if this does not work, then…*Perform Daily or Hourly Before/After Analysis.
c) *And if this does not work, then…*Perform Component Isolation Analysis.
d) *And if this does not work, then…*Perform Calibrated Simulation Analysis.
e) *Then…*Report savings and Finish Analysis.

1.2 History of M&V

1.2.1 History of Building Energy Measurement.

The history of the measurement of building energy use can be traced back to the 19th century for electricity, and earlier for fuels such as coal and wood, which were used to heat buildings.[7,8,9,10] By the 1890s, although electricity was common in many new commercial buildings, its use was primarily for incandescent lighting and, to a lesser extent, for the electric motors associated with ventilating buildings since most of the work in office buildings was carried out during daylight hours. The metering of electricity closely paralleled the spread of electricity into cities as its inventors needed to recover the cost of its production through the collection of payments from electric utility customers.[11,12] Commercial meters for the measurement of flowing liquids in pipes can be traced back to the same period, beginning with the invention of the first commercial flowmeter by Clemens Herschel in 1887, which used principles based on the pitot tube and venturi flowmeter, invented in

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[4] Claridge D.E., Turner, W.D., Liu, M., Deng, S., Wei, G., Culp, C., Chen, H., Cho, S. 2002. “Is Commissioning Once Enough?” Solutions for Energy Security and Facility Management Challenges: Proceedings of the 25th WEEC, Atlanta, GA, October 19-11, 2002, pp.29–36.

[5] Haberl, J., Lynn, B., Underwood, D., Reasoner, J., Rury, K. 2003. “Development an M&V Plan and Baseline for the Ft. Hood ESPC Project,” ASHRAE Seminar Presentation, (June).

[6] Culp, C., Hart, K.Q., Turner, B., Berry-Lewis, S. 2003. “Energy Consumption Baseline: Fairchild AFB’s Major Boiler Retrofit,” ASHRAE Seminar (January).

[7] Arnold, D. 1999. “The Evolution of Modern Office Buildings and Air Conditioning,” ASHRAE Journal, American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA, p. 40–54, (June).

[8] Donaldson, B., Nagengast, B. 1994. Heat and Cold: Mastering the Great Indoors. American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA.

[9] Cheney, M., Uth, R. 1999. Tesla: Master of Lightning. Barnes and Noble Books, New York, N.Y.

[10] Will, H. 1999. The First Century of Air Conditioning. American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA.

[11] Israel, P. 1998. Edison: A Life of Invention. John Wiley and Sons, New York, N.Y.

[12] EEI. 1981. Handbook for Electricity Metering. 8th Edition with Appendix, Edition Electric Institute, Washington, D.C.

1732 and 1797 by their respective namesakes.[13] Commercial meters for the measurement of natural gas can likewise be traced to the sale and distribution of natural gas, which paralleled the development of the electric meters.

1.2.2 History of Measurement and Verification (M&V) in the U.S.

1.2.2.1 History of Measurement and Verification (M&V)

The history of the measurement and verification of building energy use parallels the development and use of computerized energy calculations in the 1960s, with a much accelerated awareness in 1973, when the embargo on Middle East oil made energy a front page issue.[14,15] During the 1950s and 1960s, most engineering calculations were performed using slide rules, engineering tables and desktop calculators that could only add, subtract, multiply and divide. Since the public was led to believe energy was cheap and abundant,[16] the measurement and verification of the energy use in a building was limited for the most part to simple, unadjusted comparisons of monthly utility bills.

In the 1960s, several efforts were initiated to formulate and codify equations that could predict dynamic heating and cooling loads, including efforts at the National Bureau of Standards to predict temperatures in fallout shelters,[17] and the 1967 HCC program developed by a group of mechanical engineering consultants,[18] which used the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) method. The popularity of this program prompted the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) to embark on a series of efforts that eventually delivered today's modern, general purpose simulation programs[19] (i.e., DOE-2, BLAST, EnergyPlus, etc.), which utilize thermal response factors,[20,21] as well as algorithms, for simulation of the quasi-steady-state performance of primary and secondary equipment.[22] One of these efforts was to validate the hourly calculations with field measurements at the Legal Aid Building on the Ohio State University campus,[23] which is probably the first application of a calibrated, building energy simulation program.

Some of the earliest efforts to develop standardized methods for the M&V of building energy use began with efforts to normalize residential heating energy use in single-family and multi-family buildings,[24] which include

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[13] Miller, R. 1989. Flow Measurement Engineering Handbook. McGraw Hill, New York, N.Y.

[14] American Institute of Physics. 1975. "Efficient Use of Energy: The APS Studies on the Technical Aspects of the More Efficient Use of Energy," American Physical Society, New York, N.Y. (A report on the 1973 summer study at Princeton University).

[15] National Geographic. February 1981. "Special Report on Energy: Facing up to the Problem, Getting Down to Solutions," National Geographic Society, Washington, D.C.

[16] Scientific American. 1971. Energy and Power. W.H. Freeman and Company, San Francisco, CA. (A reprint of eleven articles that appeared in the September 1971 Scientific American).

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[18] APEC. 1967. HCC-heating/cooling load calculations program. Dayton, Ohio, Automated Procedures for Engineering Consultants.

[19] Ayres, M., Stamper, E. 1995. "Historical Development of Building Energy Calculations," ASHRAE Transactions, Vol. 101, Pt. 1.

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[21] Mitalas, G., Stephenson, D. 1967. "Room Thermal Response Factors," ASHRAE Transactions, Vol. 73, Pt. 2.

[22] Stoecker, W. 1971. Proposed Procedures for Simulating the Performance of Components and Systems for Energy Calculations. 2nd Edition, American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA.

[23] Sepsy, C. 1969. "Energy Requirements for Heating, and Cooling Buildings (ASHRAE RP 66-OS)," Ohio State University.

[24] Socolow, R. 1978. Saving Energy in the Home: Princeton's Experiments at Twin Rivers. Ballinger Publishing Company, Cambridge, Massachusetts. (This book contains a collection of papers that were also

the Princeton Scorekeeping Method[25] (PRISM), a forerunner to ASHRAE's Variable-based Degree Day (VBDD) calculation method. In commercial buildings, numerous methods have been reported over the years,[26,27,28] varying from weather normalization using monthly utility billing data,[29,30,31] daily and hourly methods,[32] and even dynamic inverse models using resistance-capacitance (RC) networks.[33] Procedures and methodologies to baseline energy use in commercial buildings began to appear in several publications in the 1980s[34,35,36] and the early 1990s.[37,38,39] Modeling toolkits and software have been developed that are useful in developing performance metrics for buildings, as well HVAC system components. These efforts include the Princeton Scorekeeping Software (PRISM),[40] which is useful for developing variable-based degree day models of monthy or daily data; ASHRAE's HVAC01 software for modeling primary HVAC systems such as boilers, and chillers;[41] ASHRAE's HVAC02 software for modeling secondary HVAC systems including air-handlers, blowers, cooling coils and terminal boxes;[42] ASHRAE's Research Projects 827-RP for *in-situ* measurement of chillers, pumps, and blowers;[43] Research Project 1004-RP for *in-situ* measurement of thermal storage

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published in Energy and Buildings, Vol. 1, No. 3, April).

[25] Fels, M. 1986. "Special Issue Devoted to Measuring Energy Savings: The Scorekeeping Approach," Energy and Buildings, Vol. 9, Nos. 1, 2, Elsevier Press, Lausanne, Switzerland (February/May).

[26] DOE. 1985. Proceedings of the DOE/ORNL Data Acquisition Workshop. Oak Ridge National Laboratory, Oak Ridge, TN (October).

[27] Lyberg, M. 1987. Source Book for Energy Auditors. Vols. 1, 2, International Energy Agency, Stockholm, Sweden (Report on IEA Task XI).

[28] IEA. 1990. Field Monitoring For a Purpose. International Energy Agency Workshop, Chalmers University, Gothenburg, Sweden (April).

[29] Omnicomp. 1984. Faser Software. Omnicomp, Inc., State College, PA, (monthly accounting software with VBDD capability).

[30] Eto, J. 1988. "On Using Degree-days to Account for the Effects of Weather on Annual Energy Use in Office Buildings," Energy and Buildings, Vol. 12, No. 2, pp. 113-127.

[31] SRC Systems. 1996. Metrix: Utility Accounting System. Berkeley, CA (monthly accounting software with combined VBDD/multiple regression capabilities).

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[33] Sonderegger, R. 1977. "Dynamic Models of House Heating Based on Equivalent Thermal Parameters," Ph.D. Thesis, Center for Energy and Environmental Studies, Report No. 57, Princeton University.

[34] DOE. 1985. op. cit.

[35] Lyberg, M. 1987. op. cit.

[36] IEA. 1990. op. cit.

[37] ASHRAE. 1991. Handbook of HVAC Applications, Chapter 37: Building Energy Monitoring. American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA.

[38] Haberl, J., Lopez, R. 1992. "LoanSTAR Monitoring Workbook: Workbook and Software for Monitoring Energy in Buildings," submitted to the Texas Governor's Energy Office, Energy Systems Laboratory, Texas A&M University (August).

[39] Claridge, D., Haberl, J., O'Neal, D., Heffington, W., Turner, D., Tombari, C., Roberts, M., Jaeger, S. 1991. "Improving Energy Conservation Retrofits with Measured Savings," ASHRAE Journal, Vol. 33, No. 10, pp. 14-22 (October).

[40] Fels, M., Kissock, K., Marean, M., Reynolds, C. 1995. PRISM, Advanced Version 1.0 User's Guide. Center for Energy and Environmental Studies, Princeton University, Princeton, N.J. (January).

[41] ASHRAE. 1999. HVAC01 Toolkit: A Toolkit for Primary HVAC System Energy Calculation. ASHRAE Research Project - RP 665, Lebrun, J., Bourdouxhe, J-P, Grodent, M., American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA.

[42] ASHRAE. 1993. HVAC02 Toolkit: Algorithms and Subroutines for Secondary HVAC System Energy Calculations. ASHRAE Research Project – 827-RP, Authors: Brandemuehl, M., Gabel, S., Andresen, I., American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA.

[43] Brandemuehl, M., Krarti, M., Phelan, J. 1996. "827-RP Final Report: Methodology Development to Measure In-Situ Chiller, Fan, and Pump Performance," ASHRAE Research, ASHRAE, Atlanta, GA (March).

systems;[44] Research Project 1050-RP Toolkit for Calculating Linear, Change-point Linear and Multiple-Linear Inverse Building Energy Analysis Models;[45] and Research Project 1093-RP toolkit for calculating diversity factors for energy and cooling loads.[46]

In 1989, a report by Oak Ridge National Laboratory[47] classified the diverse commercial building analysis methods into five categories, including: annual total energy and energy intensity comparisons, linear regression and component models, multiple linear regression, building simulation, and dynamic (inverse) thermal performance models. In 1997, a reorganized and expanded version of this classification appeared in the ASHRAE Handbook of Fundamentals, and is shown in
Table 1 and Table 2. In
Table 1, different methods of analyzing building energy are presented, which have been classified according to model type, including: forward, inverse, and hybrid models.[48]

In the first method, forward modeling, a thermodynamic model is created of a building using fundamental engineering principles to predict the hypothetical energy use of a building for 8,760 hours of the year, given the location and weather conditions. This requires a complete description of the building, system, or component of interest, as well as the physical description of the building geometry, geographical location, system type, wall insulation value, etc. Forward models are normally used to design and size HVAC systems, and have begun to be used to model existing buildings, using a technique referred to as calibrated simulation.

In the second method, inverse modeling, an empirical analysis, is conducted on the behavior of the building as it relates to one or more driving forces or parameters. This approach is referred to as a system identification, parameter identification or inverse modeling. To develop an inverse model, one must assume a physical configuration of the building or system, and then identify the parameter of interest using statistical analysis.[49] Two primary types of inverse models have been reported in the literature, including: steady state inverse models and dynamic inverse models. A third category, hybrid models, consists of models that have characteristics of both forward and inverse models.[50]

The simplest steady-state inverse model regresses monthly utility consumption data against average billing period temperatures. More robust methods include multiple linear regression, change-point linear regression, and Variable-Based Degree Day regressions as indicated in
Table 1. The advantage of steady-state inverse models is that their use can be automated and applied to large datasets where monthly utility billing data and average daily temperatures for the billing periods are available. Steady-state inverse models can also be applied to daily data which allows one to compensate for differences in

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[44] Haberl, J., Reddy, A., Elleson, J. 2000a. “Determining Long-Term performance of Cool Storage Systems from Short-Term Tests, Final Report,” submitted to ASHRAE under Research Project 1004-RP, Energy Systems Laboratory Report ESL-TR-00/08-01, Texas A&M University, 163 pages (August).

[45] Kissock, K., Haberl, J., Claridge, D. 2001. “Development of a Toolkit for Calculating Linear, Change-point Linear and Multiple-Linear Inverse Building Energy Analysis Models: Final Report,” submitted to ASHRAE under Research Project 1050-RP, University of Dayton and Energy Systems Laboratory (December).

[46] Abushakra, B., Haberl, J., Claridge, D., Sreshthaputra, A. 2001 “Compilation of Diversity Factors and Schedules for Energy and Cooling Load Calculations; ASHRAE Research Project 1093: Final Report,” submitted to ASHRAE under Research Project 1093-RP, Energy Systems Lab Report ESL-TR-00/06-01, Texas A&M University, 150 pages (June).

[47] MacDonald, J., Wasserman, D. 1989. “Investigation of Metered Data Analysis Methods for Commercial and Related Buildings,” Oak Ridge National Laboratory Report No. ORNL/CON-279 (May).

[48] Rabl, A. 1988. “Parameter Estimation in Buildings: Methods for Dynamic Analysis of Measured Energy Use,” Journal of Solar Energy Engineering, Vol. 110, pp. 52-66.

[49] Rabl, A., Riahle, A. 1992. “Energy Signature Model for Commercial Buildings: Test with Measured Data and Interpretation,” Energy and Buildings, Vol. 19, pp. 143-154.

[50] Gordon, J.M., Ng, K.C. 1994. “Thermodynamic Modeling of Reciprocating Chillers,” Journal of Applied Physics, Vol. 75, No. 6, March, pp. 2769-2774.

weekday and weekend use.[51] Unfortunately, steady state inverse models are insensitive to dynamic effects (i.e., thermal mass) and other variables (i.e., humidity and solar gain), and are difficult to apply to certain building types, for example buildings that have strong on/off schedule dependent loads, or buildings that display multiple change-points.

Dynamic inverse models include: equivalent thermal network analysis,[52] ARMA models,[53,54] Fourier series models,[55,56] machine learning,[57] and artificial neural networks.[58,59] Unlike steady-state inverse models, dynamic models are capable of capturing dynamic effects such as thermal mass which traditionally have required the solution of a set of differential equations. The disadvantages of dynamic inverse models are that they are increasingly complex and need more detailed measurements to "tune" the model.

Hybrid models are models that contain forward and inverse properties. For example, when a traditional fixed-schematic simulation program such as DOE-2 or BLAST (or even a component-based simplified model) is used to simulate the energy use of an existing building, one has a forward analysis method that is being used in an inverse application, i.e., the forward simulation model is being calibrated or fit to the actual energy consumption data from a building in much the same way that one fits a linear regression of energy use to temperature.

Table 2 presents information that is useful for selecting an inverse model where usage of the model (diagnostics - D, energy savings calculations - ES, design - De, and control - C), degree of difficulty in understanding and applying the model, time scale for the data used by the model (hourly - H, daily - D, monthly - M, and sub-hourly - S), calculation time, input variables used by the models (temperature - T, humidity - H, solar - S, wind - W, time - t, thermal mass - tm), and accuracy are used to determine the choice of a particular model.

METHOD	FORWARD	INVERSE	HYBRID	COMMENTS
Steady State Methods				
Simple linear regression		X		One dependent parameter, one independent parameter. May have slope and y-intercept.
Multiple linear regression		X	X	One dependent parameter, multiple independent parameters.
Modified degree day method	X			Based on fixed reference temperature of 65F.
Variable base degree day method	X			Variable reference temperatures.
Traditional ASHRAE bin method and inverse bin method	X	X	X	Hours in temperature bin times load for that bin.

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[51] Claridge, D.E., Haberl, J.S., Sparks, R., Lopez, R., Kissock, K. 1992. “Monitored Commercial Building Energy Data: Reporting the Results,” ASHRAE Transactions Symposium Paper, Vol. 98, Pt. 1, pp. 636-652.

[52] Sonderegger, R. 1977, op. cit.

[53] Subbarao, K., Burch, J., Hancock, C.E. 1990. “How to accurately measure the load coefficient of a residential building,” Journal of Solar Energy Engineering, in preparation.

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[55] Shurcliff, W.A. 1984. “Frequency Method of Analyzing a Building's Dynamic Thermal Performance,” 19 Appleton St., Cambridge, MA.

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[58] Kreider, J.F., Wang, X.A. 1991. “Artificial Neural Networks Demonstration for Automated Generation of Energy Use Predictors for Commercial Buildings,” ASHRAE Transactions, Vol. 97, Pt. 1.

[59] Kreider, J., Haberl, J. 1994. “Predicting Hourly Building Energy Usage: The Great Energy Predictor Shootout: Overview and Discussion of Results,” ASHRAE Transactions-Research, Vol. 100, Pt. 2, pp. 1104-1118 (June).

Change point models: 3 parameter (PRISM CO, HO), 4 parameter, 5 parameter (PRISM HC).		X	X	Uses daily or monthly utility billing data and average period temperatures.
ASHRAE TC 4.7 modified bin method	X		X	Modified bin method with cooling load factors.
Dynamic Methods				
Thermal network	X	X	X	Uses equivalent thermal parameters (inverse mode).
Response factors	X			Tabulated or as used in simulation programs.
Fourier Analysis	X	X	X	Frequency domain analysis convertible to time domain.
ARMA Model		X		Autoregressive Moving Average model.
ARMA Model		X		Multiple-input autoregressive moving average model.
BEVA, PSTAR	X	X	X	Combination of ARMA and Fourier series, includes loads in time domain.
Modal analysis	X	X	X	Bldg. described by diagonalized differential equation using nodes.
Differential equation		X		Analytical linear differential equation.
Computer simulation (DOE-2, BLAST)	X		X	Hourly simulation programs with system models.
Computer emulation (HVACSIM+, TRNSYS)	X		X	Sub-hourly simulation programs.
Artificial Neural Networks		X	X	Connectionist models.

Table 1: ASHRAE's 1997 Classification of Methods for the Thermal Analysis of Buildings.[60]

METHOD	USAGE (1)	DIFFICULTY	TIME SCALE: (2)	CALC. TIME	VARIABLES	ACCURACY
Simple linear regression	ES	Simple	D,M	Very Fast	T	Low
Multiple linear regression	D,ES	Moderate	D,M	Fast	T,H,S,W,t	Medium
Inverse ASHRAE bin method	ES	Moderate	H	Fast	T	Medium
Change point models.	D,ES	Moderate	H,D,M	Fast	T	Medium
ASHRAE TC 4.7 modified bin method	ES, De	Moderate	H	Medium	T,S,tm	Medium
Thermal network	D,ES,C	Complex	S,H	Fast	T,S,tm	High
Fourier Series Analysis	D,ES,C	Complex	S,H	Medium	T,H,S,W,t,tm	High
ARMA Model	D,ES,C	Complex	H	Medium	T,H,S,W,t,tm	High
Modal analysis	D,ES,C	Complex	H	Medium	T,H,S,W,t,tm	High
Differential equation	D,ES,C	Very Complex	S,H	Fast	T,H,S,W,t,tm	High
Computer Simulation (Component-based)	D,ES,C, De	Very Complex	S,H	Slow	T,H,S,W,t,tm	Medium
Computer simulation (Fixed schematic)	D,ES,De	Very Complex	H	Slow	T,H,S,W,t,tm	Medium
Computer emulation	D,C	Very Complex	S,H	Very Slow	T,H,S,W,t,tm	High
Artificial Neural Networks	D,ES,C	Complex	S,H	Medium	T,H,S,W,t,tm	High

NOTE: (1) Usage shown includes: diagnostics (D), energy savings calculations (ES), design (De), and control (C).
(2) Time scales shown are hourly (H), daily (D), monthly (M), and sub-hourly (S).
(3) Variables include: temperature (T), humidity (H), solar (S), wind (W), time (t), thermal mass (TM).

Table 2: ASHRAE's 1997 Decision Diagram for Selection of Model[61].

1.2.2.2 History of M&V Protocols in the United States

The history of measurement and verification protocols in the United States can be traced to independent M&V efforts in different regions of the country as shown in Table 3, with states such as New Jersey, California, and Texas developing protocols that contained varying procedures for measuring the energy and demand savings from retrofits to existing buildings. These efforts culminated in the development of the USDOE's 1996 North American Measurement and Verification Protocol (NEMVP),[62] which was accompanied by the USDOE's 1996 FEMP Guildelines,[63] both relied on analysis methods developed in the Texas LoanSTAR program.[64] In

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[60] ASHRAE. 1997. Handbook of Fundamentals, Chapter 30: Energy Estimating and Modeling Methods. American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA., p. 30.27 (Copied with permission).

[61] ASHRAE. 1997. op. cit., p. 30.28 (Copied with permission).

[62] USDOE. 1996. North American Energy Measurement and Verification Protocol (NEMVP). United States Department of Energy DOE/EE-0081 (March).

[63] FEMP. 1996. Standard Procedures and Guidelines for Verification of Energy Savings Obtained Under Federal Savings Performance Contracting Programs. USDOE Federal Energy Management Program (FEMP).

1997, the NEMVP was updated and republished as the International Performance Measurement and Verification Protocols (IPMVP).[65] The IPMVP was then expanded in 2001 into two volumes: Volume I covering Energy and Water Savings,[66] and Volume II covering Indoor Environmental Quality.[67] In 2003, Volume III of the IPMVP was published, which covers protocols for new construction.[68] Finally, in 2002, the American Society of Heating Refrigeration Air-conditioning Engineers (ASHRAE) released Guideline 14-2002: Measurement of Energy and Demand Savings,[69] which is intended to serve as the technical document for the IPMVP.

2003 – IPMVP-2003 Volume III (new construction)
2002 – ASHRAE Guideline 14-2002
2001 - IPMVP-2001 Volume I & II (revised and expanded IPMVP)
1998 - Texas State Performance Contracting Guidelines
1997 - IPMVP (revised NEMVP)
1996 - FEMP Guidelines
1996 - NEMVP
1995 - ASHRAE Handbook - Ch. 37 “Building Energy Monitoring”
1994 - PG&E Power Saving Partner “Blue Book”
1993 - NAESCO M&V Protocols
1993 - New England AEE M&V Protocols
1992 - California CPUC M&V Protocols
1989 - Texas LoanSTAR Program
1988 - New Jersey M&V Protocols
1985 - First Utility Sponsored Large Scale Programs to Include M&V
1985 - ORNLs “Field Data Acq. For Bld & Eqp Energy Use Monitoring”
1983 – International Energy Agency “Guiding Principles for Measurement”
1980s - USDOE funds the End-Use Load and Consumer Assessment Program (ELCAP)
1980s - First Utility Sponsored Large Scale Programs to Include M&V
1970s - First Validation of Simulations
1960s - First Building Energy Simulations on Mainframe Computers

Table 3: History of M&V Protocols

1.3 Performance Contracts

In order to reduce costs and improve the HVAC and lighting systems in its buildings, the U.S. Federal Government has turned to the private energy efficiency sector to develop methods to finance and deliver energy efficiency to the government. One of these arrangements, the performance contract, often includes a guarantee of performance, which benefits from accurate, reliable measurement and verification. In such a contract, all costs of the project (i.e., administration, measurement and verification, overhead and profit) are paid for by the energy saved from the energy or water conservation projects. In principle, this is a very

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[64] Haberl, J., Claridge, D., Turner, D., O’Neal, D., Heffington, W., Verdict, M. 2002. “LoanSTAR After 11 Years: A Report on the Successes and Lessons Learned From the LoanSTAR Program,” Proceedings of the 2nd International Conference for Enhanced Building Operation, Richardson, Texas, pp. 131–138 (October).

[65] USDOE. 1997. International Performance Measurement and Verification Protocol (IPMVP). United States Department of Energy DOE/EE-0157 (December).

[66] USDOE. 2001. International Performance Measurement and Verification Protocol (IPMVP): Volume I: Concepts and Options for Determining Energy and Water Savings. United States Department of Energy DOE/GO-102001-1187 (January).

[67] USDOE. 2001. International Performance Measurement and Verification Protocol (IPMVP): Volume II: Concepts and Practices for Improved Indoor Environmental Quality. United States Department of Energy DOE/GO-102001-1188 (January).

[68] USDOE. 2003. International Performance Measurement and Verification Protocol (IPMVP): Volume II: Concepts and Practices for Improved Indoor Environmental Quality. United States Department of Energy DOE/GO-102001-1188 (January).

[69] ASHRAE. 2002.Guideline 14: Measurement of Energy and Demand Savings. American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA (September).

attractive option for the government, since it avoids paying the initial costs of the retrofits, which would have to come from shrinking taxpayer revenues. Instead, the costs are paid over a series of years because the government agrees to pay the Energy Service Company (ESCO) an annual fee that equals the annual normalized cost savings of the retrofit (plus other charges). This allows the government to finance the retrofits by paying a pre-determined annual utility bill over a series of years, which equals the utility bill during the base year had the retrofit not occurred. In reality, because the building has received an energy conservation retrofit, the actual utility bill is reduced, which allows funding the annual fee to the ESCO without realizing any increase in the total annual utility costs (i.e., utility costs plus the ESCO fee). Once the performance contract is paid off, the total annual utility bills for the government are reduced and the government receives the full savings amount of the retrofit.

1.3.1 Definitions, Roles and Participants

There are many different types of performance contracts, which vary according to risk, and financing, including Guaranteed Savings, and Shared Savings.[70] In a Guaranteed Savings performance contract, a fixed payment is established that repays the ESCO’s debt financing of the energy conservation retrofit and any fees associated with the project. In return, the ESCO guarantees that the energy savings will cover the fixed payment to the ESCO. Hence, in a Guaranteed Savings contract, the ESCO is responsible for the majority of the project risks. In a Shared Savings performance contract, payments to the ESCO are based on an agreed-upon portion of the estimated savings generated by the retrofit. In such contracts, the M&V methods selected determine the level of risk and the responsibilities of the ESCO and the building owner. In both types of contracts, the measurement and verification of the energy savings plays a crucial role in determining payment amounts.

2 Overview of Measurement and Verification Methods

Nationally-recognized protocols for measurement and verification have evolved since the publication of the 1996 NEMVP as shown in
Table 4. This evolution reflects the consensus process that the Department of Energy has chosen as a basis for the protocols. This process was chosen to produce methods that all parties agree can be used by the industry to determine savings from performance contracts, varying in accuracy and cost from partial stipulation to complete measurement. In 1996, three M&V methods were included in the NEMVP: Option A: measured capacity with stipulated consumption; Option B: end-use retrofits, which utilized measured capacity and measured consumption; and Option C: whole-facility or main meter measurements, which utilize before after-regression models.

In 1997, Options A, B, and C were modified and relabeled, and in Option D, calibrated simulation was added. Also included in the 1997 IPMVP was a chapter on measuring the performance of new construction, which primarily utilized calibrated simulation, and a discussion of the measurement of savings due to water conservation efforts. In 2001, the IPMVP was published in two volumes: Volume I, which covers Options A, B, and C, which were redefined and relabeled from the 1997 IPMVP, and Volume II, which covers indoor environmental quality (IEQ), and includes five M&V approaches for IEQ, including: no IEQ M&V, M&V based on modeling, short-term measurements, long-term measurements, and a method based on occupant perceptions of IEQ. In 2003, the IPMVP released Volume III, which contains four M&V methods: Option A: partially measured Energy Conservation Measure (ECM) isolation; Option B: ECM isolation; Option C: whole-building comparisons; and Option D: whole-building calibrated simulation.

In 2002, ASHRAE released Guideline 14-2002: Measurement of Energy and Demand Savings, which is intended to serve as the technical document for the IPMVP. As the name implies, Guideline 14 contains approaches for measuring energy and demand savings from energy conservation retrofits to buildings. This includes three methods: 1) a retrofit isolation approach, which parallels Option B of the IPMVP; 2) a whole-building approach, which parallels Option C of the IPMVP; and 3) a whole-building calibrated simulation approach, which parallels Option D of the 1997 and 2001 IPMVP. ASHRAE’s Guideline 14 does not

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[70] Hansen, S. 1993. Performance Contracting for Energy and Environmental Systems. Fairmont Press, Lilburn, GA, pp. 99-100.

explicitly contain an approach that parallels Option A in the IPMVP, although several of the retrofit isolation approaches use partial measurement procedures, as will be discussed in a following section.

1996 NEMVP	1997 IPMVP	2001/2003 IPMVP	2002 ASHRAE GUIDELINE 14
OPTION A: Measured Capacity Stipulated Consumption	OPTION A: End-use Retrofits: Measured Capacity, Stipulated Consumption	VOLUME I: OPTION A: Partially Measured Retrofit Isolation	
OPTION B: End-use Retrofits: Measured Capacity, Measured Consumption	OPTION B: End-use Retrofits: Measured Capacity, Measured Consumption	VOLUME I: OPTION B: Retrofit Isolation	RETROFIT ISOLATION APPROACH
OPTION C: Whole-facility or Main Meter Measurement	OPTION C: Whole-facility or Main Meter Measurement	VOLUME I: OPTION C: Whole-building	WHOLE-BUILDING APPROACH
	OPTION D: Calibrated Simulation	VOLUME I: OPTION D: Calibrated Simulation	WHOLE-BUILDING CALIBRATED SIMULATION APPROACH
		VOLUME II: IEQ M&V 5 Approaches	
	Measurement and Verification of New Buildings	VOLUME III: New Construction	
	EXAMPLE: Water Projects		

Table 4: Evolution of M&V Protocols in the United States.

2.1 M&V Methods: Existing Buildings

In general, a common theme between the NEMVP, IPMVP and ASHRAE's Guideline 14-2002 is that M&V methods for measuring energy and demand savings in existing building are best represented by the following three approaches: retrofit isolation approach, a whole-building approach, and a whole-building calibrated simulation approach. Similarly, the measurement of the performance of new construction, renewables, and water use utilize one or more of these same methods.

2.1.1 Retrofit Isolation Approach

The retrofit isolation approach is best used when end use capacity, demand or power can be measured during the baseline period and after the retrofit for short-term period(s) or continuously over the life of the project. This approach can use continuous measurement of energy both before and after the retrofit. Likewise, periodic, short-term measurements can be used during the baseline and after the retrofit to determine the retrofit savings. Often such short-term measurements are accompanied by periodic inspections of the equipment to assure that the equipment is operating as specified. In most cases, energy use is calculated by developing representative models of the isolated component load (i.e., the kW or Btu/hr) and energy end-use (i.e., the kWh or Btu).

2.1.1.1 Classifications of Retrofits

According to ASHRAE's Guideline 14-2002, retrofit isolation approach, components or end-uses can be classified according to the following definitions.[71]

1. Constant Load, Constant use. Constant load, constant use systems consist of systems where the energy used by the system is constant (i.e., varies by less than 5%) and the use of the system is constant (i.e., varies by less than 5%) through both the baseline and post-retrofit period.

2. Constant Load, Variable use. Constant load, variable use systems consist of systems where the energy used by the system is constant (i.e., varies by less than 5%) but the use of the system is variable (i.e., varies by more than 5%) through either the baseline or post-retrofit period.

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[71] ASHRAE. 2002. op. cit., pp. 27–30.

<u>3. Variable Load, Constant use.</u> Variable Load, constant use systems consist of systems where the energy used by the system is variable (i.e., varies by more than 5%) but the use of the system is constant (i.e., varies by less than 5%) through either the baseline or post-retrofit period.

<u>4. Variable Load, Variable use.</u> Variable Load, variable use systems consist of systems where the energy used by the system is variable (i.e., varies by more than 5%) and the use of the system is variable (i.e., varies by more than 5%) through either the baseline or post-retrofit period.

Use of these classifications then allows for a simplified decision table (Table 5) to be used in determining which type of retrofit-isolation procedure to use. For example, in the first row (i.e., a CL/TS-pre-retrofit to CL/TS-post-retrofit), if a constant load with a known or timed schedule is replaced with a new device that has a reduced constant load and a known or constant schedule, then the pre-retrofit and post-retrofit metering can be performed with one-time load measurement(s). Contrast this with the last row (i.e., a VL/VS-pre-retrofit to VL/VS-post-retrofit), if a variable load with a timed or variable schedule is replaced with a new device that has a reduced variable load and a variable schedule, then the pre-retrofit and post-retrofit metering should use continuous or short-term measurement that are sufficient in length to allow for the characterization of the performance of the component to be accomplished with a model (e.g., regression, or engineering model).

Pre- Retrofit	**Retrofit changes**	**Required metering**	
		Pre-retrofit	Post-retrofit
CL/TS	Load but still CL	One time load measurement	One time load measurement
CL/TS	Load to VL	One time load measurement	Sufficient load measurements to characterize load
CL/TS	Schedule but still TS	One time load measurement (either pre- or post-retrofit)	
CL/TS	Schedule to VS	One time load measurement (either pre- or post-retrofit)	Sufficient measurement of runtime
CL/TS	Load but still CL and schedule but still TS	One time load measurement	One time load measurement
CL/TS	Load to VL and schedule but still TS	One time load measurement	Sufficient load measurements to characterize load
CL/TS	Load but still CL and schedule to VS	One time load measurement	One time load measurement and sufficient measurement of runtime
CL/TS	Load to VL and schedule to VS	One time load measurement	Sufficient load measurements to characterize load
CL/VS	Load but still CL	One time load measurement and sufficient measurement of runtime	One time load measurement and sufficient measurement of runtime
CL/VS	Load to VL	One time load measurement and sufficient measurement of runtime	Sufficient load measurements to characterize load
CL/VS	Schedule to TS	One time load measurement (either pre- or post-retrofit) and sufficient measurement of runtime	
CL/VS	Schedule but still VS	One time load measurement (either pre- or post-retrofit) and sufficient measurement of runtime	Sufficient measurement of runtime
CL/VS	Load but still CL and schedule to TS	One time load measurement and sufficient measurement of runtime	One time load measurement
CL/VS	Load to VL and schedule but still TS	One time load measurement and sufficient measurement of runtime	Sufficient load measurements to characterize load
CL/VS	Load but still CL and schedule to VS	One time load measurement and sufficient measurement of runtime	One time load measurement and sufficient measurement of runtime
CL/VS	Load to VL and schedule but still VS	One time load measurement and sufficient measurement of runtime	Sufficient load measurements to characterize load
VL/TS or VS	Load to CL	Sufficient load measurements to characterize load	One time load measurement and sufficient measurement of runtime
VL/TS or VS	Load but still VL	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load
VL/TS or VS	Schedule still or to TS	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load
VL/TS or VS	Schedule to or still VS	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load
VL/TS or VS	Load to CL and schedule still or to TS	Sufficient load measurements to characterize load	One time load measurement
VL/TS or VS	Load but still VL and schedule still or to TS	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load
VL/TS or VS	Load to CL and schedule to or still VS	Sufficient load measurements to characterize	One time load measurement and sufficient

		load	measurement of runtime
VL/TS or VS	Load but still VL and schedule to or still VS	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load

CL = constant load
TS = timed (known) schedule
VL = variable load
VS = variable (unknown) schedule

Table 5: Metering Requirements to Calculate Energy and Demand Savings From the ASHRAE Guideline 14-2002.[72]

2.1.1.2 Detailed Retrofit Isolation Measurement and Verification Procedures

Appendix E of ASHRAE's Guideline 14-2002 contains detailed retrofit isolation procedures for the measurement and verification of savings, including pumps, fans, chillers, boilers and furnaces, lighting, and large and unitary HVAC systems. In general, the procedures were drawn from the previous literature, including ASHRAE's Research Project 827-RP[73] (i.e., pumps, fans, chillers), various published procedures for boilers and furnaces,[74,75,76,77,78,79,80] lighting procedures, and calibrated HVAC calibration simulations.[81,82] A review of these procedures, which vary from simple one-time measurements, to complex, calibrated air-side psychrometric models, is described in the following sections.

2.1.1.2.1 Pumps

Most large HVAC systems utilize electric pumps for moving heating/cooling water from the building's primary systems (i.e., boiler or chiller) to the building's secondary systems (i.e., air-handling units, radiators, etc.) where it can condition the building's interior. Such pumping systems use different types of pumps, varying control strategies, and piping layouts. Therefore, the characterization of pumping electric power depends on the system design and control method used. Pumping systems can be characterized by the three categories shown in
Table 6.[83]
Table 7 shows the six pump testing methods, including the required measurements, applications and procedures steps.

ASHRAE's Research Project 827-RP[84] developed six *in-situ* methods for measuring the performance of pumps of varying types and controls. To select a method, the user needs to determine the pump system type and control, and the desired level of uncertainty, cost, and degree of intrusion. The user also needs to record the pump and motor data (i.e., manufacturer, model and serial number), fluid characteristics and operating

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[72] Ibid, p. 30 (Copied with permission).

[73] Brandemuehl et al. 1996. op. cit.

[74] Wei, G. 1997. "A Methodology for In-situ Calibration of Steam Boiler Instrumentation," MS Thesis, Mechanical Engineering Department, Texas A&M University, August.

[75] Dukelow, S.G. 1991. The Control of Boilers. Research Triangle Park, NC: Instrument Society of America.

[76] Dyer, F.D., Maples, G. 1981. Boiler Efficiency Improvement. Boiler Efficiency Institute. Auburn, AL.

[77] Garcia-Borras, T. 1983. Manual for Improving Boiler and Furnace Performance. Houston, TX: Gulf Publishing Company.

[78] Aschner, F.S. 1977. Planning Fundamentals of Thermal Power Plants. Jerusalem, Israel: Israel Universities Press.

[79] ASME 1974 Performance Test for Steam Units -- PTC 4.1a 1974.

[80] Babcock and Wilcox. 1992. Steam: Its generation and Use. Babcock and Wilcox, Barberton, Ohio, ISBN 0-9634570-0-4.

[81] Katipamula, S., Claridge, D. 1992. "Monitored Air Handler Performance and Comparison with a Simplified System Model," ASHRAE Transactions, Vol. 98, Pt. 2, pp. 341-351.

[82] Liu, M., Claridge, D. 1995. "Application of Calibrated HVAC Systems to Identify Component Malfunctions and to Optimize the Operation and Control Schedules," ASME/JSME International Solar Energy Conference, pp. 209-217.

[83] ASHRAE. 2002. op. cit., p. 144.

[84] Brandemuehl, et al. 1996. op. cit.

conditions. The first two methods (i.e., single-point and single-point with a manufacturer's curve) involve testing at a single operating point. The third and fourth procedures involve testing at multiple operating points under imposed system loading. The fifth method also involves multiple operating points, in this case obtained through short-term monitoring of the system without imposed loading. The sixth procedure operates the pump with the fluid flow path completely blocked. While the sixth procedure is not useful for generating a power versus load relationship, it can be used to confirm manufacturer's data or to identify pump impeller diameter. A summary of the methods is provided below. Additional details can be found by consulting ASHRAE's Guideline 14-2002.

2.1.1.2.1.1 Constant Speed and Constant Volume Pumps

Constant volume pumping systems use three-way valves and bypass loops at the end-use or at the pump. As the load varies in the system, pump pressure and flow are held relatively constant, and the pump input power remains nearly constant. Because pump motor speed is constant, constant volume pumping systems have a single operating point. Therefore, measuring the power use at the operating point (i.e., a single point measurement) and the total operating hours are enough to determine annual energy use.

2.1.1.2.1.2 Constant Speed and Variable Volume Pumps

Variable pumping systems with constant speed pumps use two-way control valves to modulate flow to the end-use as required. In constant speed variable volume pumping systems, the flow varies along the pump curve as the system pressure drop changes in response to the load. In some cases, a bypass valve may be modulated if system differential pressure becomes too large. Such systems have a single possible operating point for any given flow, as determined by the pump curve at that flow rate. In such systems, the second and third testing methods can be used to characterize the pump's energy use at varying conditions. In the second procedure, measurements of *in-situ* power use are performed at one flow rate and manufacturer's data on the pump, motor, and drive system are used to create a part load power use curve. In the third testing method, *in-situ* measurements are made of the electricity use of the pump with varying loads imposed on the system using existing control, discharge, or balancing valves. The forth and fifth methods can also be used to characterize the pump electricity use. Using one of these methods, the part load power use curve and a representative flow load frequency distribution are used to determine annual energy use.

2.1.1.2.1.3 Variable Speed and Variable Volume Pumps

Like the constant speed variable volume system, flow to the zone loads is typically modulated using two-way control valves. However, in variable speed variable volume pumping systems, a static pressure controller is used to adjust pump speed to match the flow load requirements. In such systems, the operating point cannot be determined solely from the pump curve and flow load because a given flow can be provided at various pressures or speeds. Furthermore, the system design and control strategy place constraints on either the pressure or flow. Such systems have a range of system curves which call for the same flow rate, depending on the pumping load. 827-RP provides two options (i.e., multiple point with imposed loads and short-term monitoring) for accurately determining the *in-situ* part load power use. In both cases, the characteristics of the *in-situ* test include the pump and piping system (piping, valves, and controllers); therefore, the control strategy is included within the data set. In the fourth method (i.e., multiple point with imposed load at the zone), the pump power use is measured at a range of imposed loads . These imposed loads are done at the zone level to account for the *in-situ* control strategy and system design. In the fifth method (i.e., multiple point through short-term monitoring), the pump system is monitored as the building experiences a range of thermal loads, with no artificial imposition of loads. If the monitored loads reflect the full range of loads, then an accurate part load power curve can be developed that represents the full range of annual load characteristics. For methods #4 and #5, the measured part load power use curves and flow load frequency distribution are used to determine annual energy use.

	Pumping System:

Test Method:		**Constant Speed, Constant Volume**	**Constant Speed, Variable Volume**	**Variable Speed, Variable Volume**
1.	Single Point	✓		
2.	Single Point with Manufacturer's Pump Curve		✓	
3.	Multiple Point with Imposed Loads at Pump		✓	
4.	Multiple Point with Imposed Loads at Zone		✓	✓
5.	Multiple Point through Short Term Monitoring		✓	✓
6.	No-Flow Test for Pump Characteristics	✓	✓	✓

Table 6: Applicability of Test Methods to Common Pumping Systems From the ASHRAE Guideline 14-2002.[85]

METHOD	**PUMPS**
Method #1: Single Point Test	Measure: i) volumetric flow rate, ii) coincident RMS power, iii) differential pressure, iv) and rotational speed while the pump is at typical operating conditions. Applications: Constant volume constant speed pumping systems. Used to confirm design operating conditions and pump and system curves. Steps: • Operate pump at typical existing operating conditions for the system. • Measure pump suction and discharge pressure, or differential pressure. • Measure pump capacity. • Measure motor RMS power input. • Measure speed. • Calculate pump and energy characteristics.
Method #2: Single Point Test with Manufacturer's Curve	Measure: i) volumetric flow rate, ii) coincident RMS power, iii) differential pressure, iv) rotational speed while the pump is at typical operating conditions. Applications: Variable volume constant speed pumping systems. Used with manufacturer's data on the pump, motor, and drive system to determine power at other operating points. Steps: • Obtain manufacturer's pump performance curves. • Operate pump at typical existing operating conditions. • Measure pump suction and discharge pressure, or differential pressure. • Measure pump capacity. • Measure motor RMS power input. • Measure speed. • Calculate pump and energy characteristics.
Method #3: Multiple Point Test with Imposed Loads at Pump or Fan	Measure: i) volumetric flow rate and ii) coincident RMS power while the pump is at operated at a range of flow load conditions as prescribed in the test procedures. Applications: Variable volume constant speed pumping systems. The loads are imposed downstream of the pump with existing control valves. Pump operation follows the pump curve. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation. Steps: • Operate pump with system configuration set for maximum flow. • Measure pump capacity. • Measure motor RMS power input. • Change system configuration to reduce flow and repeat measurement steps 2 and 3. • Calculate pump and energy characteristics.
Method #4: Multiple Point Test with Imposed Loads at Zone	Measure: i) volumetric flow rate and ii) coincident RMS power for a range of building or zone thermal loads as prescribed in the test procedures. Applications: Variable volume systems. The loads are imposed on the building or zones such that the system will experience a broad range of flow rates. The existing pump variable speed control strategy is allowed to operate. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation. Steps: • Operate pump with system configured for maximum flow rate. • Measure pump capacity. • Measure motor RMS power input. • Change system configuration and repeat measurement steps 2 and 3. • Calculate pump and energy characteristics.

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[85] ASHRAE. 2002. op cit., p. 144, (Copied with permission).

Method #5: Multiple Point Test through Short Term Monitoring	Measure: i) volumetric flow rate and ii) coincident RMS power for a range of building or zone thermal loads as prescribed in the test procedures. Applications: Variable volume variable speed systems. A monitoring period must be selected such that the system will experience a broad range of loads and pump flow rates. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation. Steps: • Choose appropriate time period for test. • Monitor pump operation and record data values for pump capacity and motor RMS power input. • Calculate pump and energy characteristics.
Method #6: No-Flow Test for Pump Characteristics	Measure: i) differential pressure at zero flow conditions (shut-off head) and compare to manufacturer's pump curves to determine impeller size. Applications: All types of centrifugal pumps (not recommended for use on positive displacement pumps) Steps: • Run pump at design operating conditions and close discharge valve completely. • Measure pump suction and discharge pressure, or differential pressure. • Measure speed. • Calculate shut-off head. • Compare shut-off head with manufacturer's pump performance curve to determine and/or verify impeller diameter.

Table 7: Pump Testing Methods From ASHRAE Guideline 14-2002.[86]

2.1.1.2.1.4 Calculation of Annual Energy Use

Once the pump performance has been measured, the annual energy use can be calculated using the following procedures, depending upon whether the system is a constant volume or variable volume pumping system. Savings are then calculated by comparing the annual energy use of the baseline with the annual energy use of the post-retrofit period.

Constant Volume Constant Speed Pumping Systems. In a constant volume, constant speed pumping system, the volume of the water moving through the pump is almost constant, and, therefore, the power load of the pump is virtually constant. The annual energy calculation is, therefore, a constant times the frequency of the operating hours of the pump.

$$E_{annual} = T * P$$

where:

T = annual operating hours
P = equipment power input

Variable Volume Pumping Systems. For variable volume pumping systems, the volume of water moving through the pump varies over time, hence, the power demand of the pump and motor varies. The annual energy use then becomes a frequency distribution of the load times the power associated with each of the bins of operating hours. *In-situ* testing is used to determine the power associated with the part load power use.

$$E_{annual} = \sum_i \left(T_i * P_i\right)$$

where:

i = bin index, as defined by the load frequency distribution
T_i = number of hours in bin i
P_i = equipment power use at load bin I

2.1.1.2.2 Fans

Most large HVAC systems utilize fans or air-handling units to deliver heating and cooling to the building's interior. Such air-handling systems use different types of fans, varying control strategies, and duct layouts.

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[86] ASHRAE. 2002. op. cit., pp.144-147 (Copied with permission).

Therefore, the characterization of fan electric power depends on the system design and control method used. Fan systems can be characterized by the three categories shown in Table 8.[87]

In a similar fashion as pumping systems, ASHRAE's Research Project 827-RP developed five *in-situ* methods for measuring the performance of fans of varying types and controls. To select a method, the user needs to determine the system type and control and the desired level of uncertainty, cost, and degree of intrusion. The user also needs to record the fan and motor data (i.e., manufacturer, model and serial number), as well as the operating conditions (i.e., temperature, pressure and humidity of the air stream). The first two methods (i.e., single-point and single-point with a manufacturer's curve) involve testing at a single operating point. The third and fourth procedures involve testing at multiple operating points under imposed system loading. The fifth method also involves multiple operating points, in this case obtained through short term monitoring of the system without imposed loading. Additional details about fan testing procedures can be found by consulting ASHRAE's Guideline 14-2002.

	Fan System:		
Test Method:	**Constant Speed, Constant Volume**	**Constant Speed, Variable Volume**	**Variable Speed, Variable Volume**
1. Single Point Test	✓		
2. Single Point with Manufacturer's Fan Data		✓	
3. Multiple Point with Imposed Loads at Fan		✓	
4. Multiple Point with Imposed Loads at Zone		✓	✓
5. Multiple Point through Short Term Monitoring		✓	✓

Table 8: Applicability of Test Methods to Common Fan Systems From the ASHRAE Guideline 14-2002.[88]

METHOD	**FANS**
Method #1: Single Point Test	Measure: i) volumetric flow rate, ii) coincident RMS power use, iii) fan differential pressure, and iiii) fan rotational speed while the fan is at typical operating conditions. Applications: Constant volume fan systems. Data are used to confirm design operating conditions and fan and system curves. Steps: • Operate fan at typical existing operating conditions for the system. • Measure fan inlet and discharge pressure or (preferably) differential pressure. • Measure fan flow capacity. • Measure motor RMS power input. • Measure fan speed. • Calculate fan and energy characteristics.
Method #2: Single Point Test with Manufacturer's Curve	Measure: i) volumetric flow rate, ii) coincident RMS power use, iii) fan differential pressure, and iv) fan rotational speed while the fan is at typical operating conditions. Applications: Variable volume systems without fan control. Data are used with manufacturer's data on the fan, motor, and drive system and engineering principles to determine power at other operating points. Steps: • Obtain manufacturer's fan performance curves. • Operate fan at typical existing operating conditions. • Measure fan inlet and discharge pressure, or differential pressure. • Measure fan flow capacity. • Measure motor RMS power input. • Measure fan speed. • Calculate fan and energy characteristics.
Method #3: Multiple Point Test with Imposed Loads at Pump or Fan	Measure: i) volumetric flow rate and ii) coincident RMS power while the fan is at operated at a range of flow rate conditions as prescribed in the test procedures. Applications: Variable volume systems without fan control. The loads are imposed downstream of the fan with existing dampers. Fan operation follows the fan curve. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation.

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[87] ASHRAE. 2002. op. cit., p. 144.

[88] Ibid, p. 148 (Copied with permission).

	Steps: • Operate fan with system configuration set for maximum flow. • Measure fan flow capacity. • Measure motor RMS power input. • Change system configuration to reduce flow and repeat measurement steps 2 and 3. • Calculate fan and energy characteristics.
Method #4: Multiple Point Test with Imposed Loads at Zone	Measure: i) volumetric flow rate and ii) coincident RMS power use while the fan is operated at a range of flow rate conditions as prescribed in the test procedures. Applications: Variable volume systems. Thermal loads are imposed at the building or zone level such that the system will experience a broad range of flow rates. The existing fan variable speed control strategy is allowed to operate. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation. Steps: • Operate fan with system configured for maximum flow rate. • Measure fan capacity. • Measure motor RMS power input. • Change system configuration and repeat measurement steps 2 and 3. • Calculate fan and energy characteristics.
Method #5: Multiple Point Test through Short Term Monitoring	Measure: i) volumetric flow rate and ii) coincident RMS power while the fan operates at a range of flow rates. Applications: Variable volume systems. The range of flow rates will depend on the building or zones experiencing a wide range of thermal loads. A time period must be selected such that the system will experience a broad range of loads and fan flow rates. The existing fan variable speed control strategy is allowed to operate. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation. Steps: • Choose appropriate time period for test. • Monitor fan operation and record data values for fan capacity and motor RMS power input. • Calculate fan and energy characteristics.

Table 9: Fan Testing Methods From ASHRAE Guideline 14-2002.[89]

2.1.1.2.2.1 Calculation of Annual Energy Use

Once the fan performance has been measured, the annual energy use can be calculated using the following procedures, depending upon whether the system is a constant volume or variable volume system. Savings are then calculated by comparing the annual energy use of the baseline with the annual energy use of the post-retrofit period.

Constant Volume Fan Systems. In a constant volume system the volume of the air moving across the fan is almost constant, and, therefore, the power load of the fan is virtually constant. The annual energy calculation is, therefore, a constant times the frequency of the operating hours of the fan.

$$E_{annual} = T * P$$

where:

T = annual operating hours
P = equipment power input

Variable Volume Systems. For variable volume systems, the volume of the air being moved by the fan varies over time, hence, the power demand of the fan and motor varies. The annual energy use then becomes a frequency distribution of the load times the power associated with each of the bins of operating hours. *In-situ* testing is used to determine the power associated with the part load power use.

$$E_{annual} = \sum_i \left(T_i * P_i\right)$$

where:

i = bin index, as defined by the load frequency distribution
T_i = number of hours in bin i

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[89] ASHRAE. 2002. op.cit., pp.147-149, (Copied with permission).

P_i = equipment power use at load bin I

2.1.1.2.3 Chillers

In a similar fashions as pumps and fans, *in-situ* chiller performance measurements have been also been developed as part of ASHRAE Research Project 827-RP. These models provide useful performance testing methods to evaluate annual energy use and peak demand characteristics for installed water-cooled chillers and selected air-cooled chillers. These procedures require short-term testing of the part load performance of an installed chiller system over a range of building thermal loads and coincident ambient conditions. The test methods determine chiller power use at varying thermal loads using thermodynamic models or statistical models with inputs from direct measurements, or manufacturer's data. With these models, annual energy use can be determined using the resultant part load power use curve with a load frequency distribution. Such models are capable of calculating the chiller power use as a function of the building thermal load, evaporator and condenser flow rates, entering and leaving chilled water temperatures, entering condenser water temperatures, and internal chiller controls. ASHRAE’s Guideline 14-2002 describes two models for calculating the power input of a chiller, including simple and temperature dependent thermodynamic models.[90,91,92] A third method, which uses a tri-quadratic regression model such as those found in the DOE-2 simulation program,[93,94,95,96,97] also provides acceptable performance models, provided that measurements are made over the full operating range.

2.1.1.2.3.1 Simple Thermodynamic Model

Both the simple thermodynamic model and the temperature-dependent thermodynamic model express chiller efficiency as 1/COP because it has a linear relationship with 1/(evaporator load). The simpler version of the chiller model developed predicts a linear relationship between 1/COP and $1/Q_{evap}$, which is independent of the evaporator supply temperature or condenser temperature returning to the chiller. The full form of simple thermodynamic model is shown in the equation below.

$$\frac{1}{COP} = -1 + \left(T_{cwRT} \big/ T_{chwST} \right) + \left(\frac{1}{Q_{evap}} \right) \left(\frac{q_{evap} T_{cwRT}}{T_{chwST}} - q_{cond} \right) + f_{HX}$$

where:

T_{cwRT} = Entering (return) condenser water temperature (Kelvin)
T_{chwST} = Leaving (supply) evaporator water temperature (Kelvin)
Q_{evap} = Evaporator load
q_{evap} = rate of internal losses in evaporator
q_{cond} = rate of internal losses in condenser

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[90] Gordon, J.M., Ng, K.C. 1994. op. cit.

[91] Gordon, J.M., Ng, K.C. 1995. “Predictive and diagnostic aspects of a universal thermodynamic model for chillers,” International Journal of Heat Mass Transfer, 38(5), p. 807.

[92] Gordon, J.M., Ng, K.C., Chua, H.T. 1995. “Centrifugal chillers: thermodynamic modeling and a diagnostic case study,” International Journal of Refrigeration, 18(4), p.253.

[93] LBL. 1980. DOE-2 User Guide, Ver. 2.1. Lawrence Berkeley Laboratory and Los Alamos National Laboratory, Rpt No. LBL-8689 Rev. 2; DOE-2 User Coordination Office, LBL, Berkeley, CA.

[94] LBL. 1981. DOE-2 Engineers Manual, Ver. 2.1A, Lawrence Berkeley Laboratory and Los Alamos National Laboratory, Rpt No. LBL-11353; DOE-2 User Coordination Office, LBL, Berkeley, CA.

[95] LBL. 1982. DOE-2.1 Reference Manual Rev. 2.1A. Lawrence Berkeley Laboratory and Los Alamos National Laboratory, Rpt No. LBL-8706 Rev. 2; DOE-2 User Coordination Office, LBL, Berkeley, CA. LBL.

[96] LBL. 1989. DOE-2 Supplement, Ver 2.1D. Lawrence Berkeley Laboratory, Rpt No. LBL-8706 Rev. 5 Supplement. DOE-2 User Coordination Office, LBL, Berkeley, CA.

[97] Haberl, J.S., Reddy, T.A., Figueroa, I., Medina, M. 1997. “Overview of LoanSTAR Chiller Monitoring and Analysis of In-Situ Chiller Diagnostics Using ASHRAE RP827 Test Method,” Proceedings of the PG&E Cool Sense National Integrated Chiller Retrofit Forum (September).

f_{HX} = dimensionless term[98].

This equation reduces to a simple form that allows for the determination of two coefficients using linear regression, which is shown in the following equation:

$$\frac{1}{COP} = c_1\left(\frac{1}{Q_{evap}}\right) + c_0$$

In this simplified form, the coefficient c_1 characterizes the internal chiller losses, while the coefficient c_0 combines the other terms of the simple model. The COP figure of merit can be converted into conventional efficiency measures of COP or kW per ton using the following relationships:

Coefficient of Performance (COP):

$$COP = \frac{kW\ refrigeration\ effect}{kW\ input}$$

Energy Efficiency Ratio (EER):

$$EER = \frac{Btu/hr\ refrigeration\ effect}{Watt\ input} = 3.412\ COP$$

Power per Ton (kW/ton):

$$kW/ton = \frac{kW\ input}{tons\ refrigeration\ effect} = 12/EER$$

The simple thermodynamic model can be determined with relatively few measurements of the chiller load (evaporator flow rate, entering and leaving chilled water temperatures) and coincident RMS power use. Unfortunately, variations in the chilled water supply (i.e., the temperature of the chilled water leaving the evaporator) and the condenser water return temperature are not considered. Hence, this model is best used with chiller systems that maintain constant temperature control of evaporator and condenser temperatures. In systems with varying temperatures, a temperature-dependent thermodynamic model, or tri-quadratic model, yields a more accurate performance prediction.

2.1.1.2.3.2 Temperature-Dependent Thermodynamic Model

The temperature-dependent thermodynamic model includes the losses in the heat exchangers of the evaporator and condenser, which are expressed as a function of the chilled water supply and condenser water return temperatures. The resulting expression uses three coefficients (A_0, A_1, A_2), which are found with linear regression, as shown in the equation that follows:

$$\frac{1}{COP} = -1 + \left(T_{cwRT}/T_{chwST}\right) + \frac{-A_0 + A_1\left(T_{cwRT}\right) - A_2\left(T_{cwRT}/T_{chwST}\right)}{Q_{evap}}$$

Use of this temperature dependent thermodynamic model requires the measurement of the chiller load (i.e., evaporator flow rate, entering and leaving chilled water temperatures), coincident RMS power use, and condenser water return temperature. Since this model is sensitive to varying temperatures, it is applicable to a wider range of chiller systems.

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[98] According to Gordon et al. 1995. f_{HX} is a dimensionless term that is normally negligible.

To use the temperature dependent model, measured chiller thermal load, coincident RMS power use, chilled water supply temperature, and condenser water return temperatures are used to calculate the three coefficients (A_0, A_1, A_2).

To determine A_2 the following equation is plotted against T_{cwRT}/T_{chwST} (Kelvin), with value of A_2 being determined from the regression lines, which should resemble a series of straight parallel lines, one for each condenser temperature setting.

$$\alpha = \left(\frac{1}{COP} + 1 - \left({T_{cwRT}}\big/{T_{chwST}} \right) \right) Q_{evap}$$

The coefficients A_0 and A_1 are determined by plotting β from the next equation, using the already determined value of A_2, versus the condenser water return temperature T_{cwRT} (Kelvin). This should result in a group of data points forming a single straight line. The slope of the regression line determines the value of coefficient A_1 while the intercept determines the value of coefficient A_0.

$$\beta = \left(\frac{1}{COP} + 1 - \left({T_{cwRT}}\big/{T_{chwST}} \right) \right) Q_{evap} + A_2 \left({T_{cwRT}}\big/{T_{chwST}} \right)$$

After A_0, A_1, and A_2 have been determined using α and β from the equations above, the 1/COP can be calculated and used to determine the chiller performance over a wide range of measured input parameters of chiller load, chilled water supply temperature, and condenser water return temperature.

2.1.1.2.3.3 Quadratic Chiller Models

Chiller performance models can also be calculated with quadratic models, which can include models that express the chiller power use as a function of: the chiller load (quadratic); the chiller load and chilled water supply temperature (bi-quadratic); or the chiller load, evaporator supply temperature and condenser return temperature (tri-quadratic). Such models use the quadratic functional form used in the DOE-2 energy simulation program to model part-load equipment and plant performance characteristics. Two examples of quadratic models are shown below, one for a monitoring project where chiller electricity use, chilled water production, chilled water supply temperature, and condenser water temperature returning to the chiller were available, which uses a tri-quadratic model as follows:

$$\begin{aligned} kW/ton = {} & a + b \times Tons + c \times T_{cond} + d \times T_{evap} + e \times Tons^2 + f \times T_{cond}^2 \\ & + g \times T_{evap}^2 + h \times Tons \times T_{cond} + I \times T_{evap} \times Tons \\ & + j \times T_{cond} \times T_{evap} + k \times Tons \times T_{cond} \times T_{evap}. \end{aligned}$$

In a second example, chiller electricity use is modeled with a bi-quadratic model that includes only the chilled water production, and chilled water supply temperature, which reduces to the following form. Either model can easily be calculated from field data in a spreadsheet using multiple linearized regression.

$$kW/ton = a + b \times Tons + c \times T_{evap} + d \times Tons^2 + e \times T_{evap}^2 + f \times T_{evap} \times Tons$$

2.1.1.2.3.4 Example: Quadratic Chiller Models

An example of a quadratic chiller performance analysis model is provided from hourly measurements that were taken to determine the baseline model of a cooling plant at an Army base in Texas. Figure 1 shows the time series data that were recorded during June and August of 2002. The upper trace is the chiller thermal load (tons), and the lower trace is the ambient temperature during this period. Figure 2 shows a time series plot of the recorded temperatures of the condenser water returning to the chiller (upper trace), and the chilled water supply temperatures (lower trace). In Figure 3 and Figure 4, the performance of the chiller is shown as the chiller efficiency (i.e., kW/ton) versus the chiller load (tons). In Figure 3, linear ($R^2 = 34.3\%$) and quadratic

(R^2 = 53.4%) models of the chiller are superimposed over the measured data from the chiller to illustrate how a quadratic model fits the chiller data. In Figure 4, a tri-quadratic model (R^2 = 83.7%) is shown superimposed over the measured data.

A quick inspection of the R^2 goodness-of-fit indicators for the linear, quadratic and tri-quadratic models begins to shed some light on how well the models are fitting the data. However, one must also inspect how well the model is predicting the chiller performance at the intended operation points. For example, although a linear model has an inferior R^2 when compared to a quadratic model, for this particular chiller, it gives similar performance values for cooling loads ranging from 200 to 450 tons. Choosing the quadratic model improves the prediction of the chiller performance for values below 200 tons. However, it significantly under predicts the kW/ton at 350 tons and over-predicts the kW/ton at values over 500 tons. Hence, both models should be used with caution.

The tri-quadratic model has an improved R^2 of 83.7% and does not seem to contain any ranges where the model's bias is significant from the measured data (excluding the few stray points which are caused by transient data). Therefore, in the case of this chiller, the additional effort to gather and analyze the chiller load against the chilled water supply temperature and condenser water return temperature is well justified.

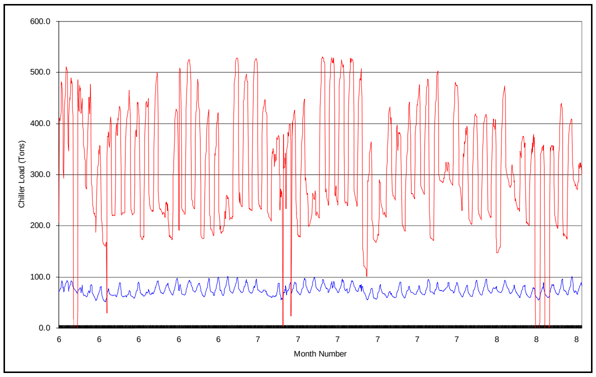

Figure 1: Example chiller analysis. Time series plot of chiller load (upper trace, tons in red) and ambient temperature (lower trace, degrees F in blue).

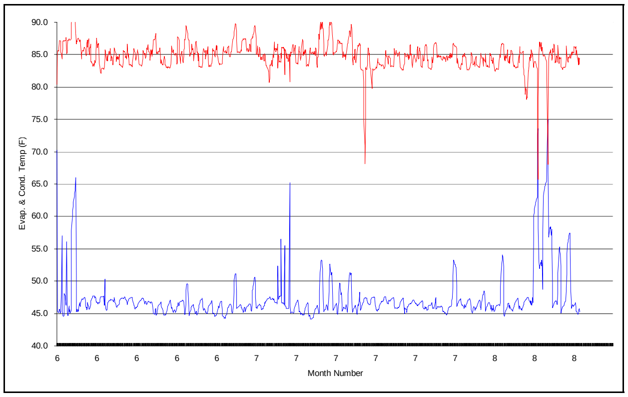

Figure 2: Example chiller analysis. Time series plot of condenser water return temperature (upper trace, degrees F in red) and chilled water supply temperature (lower trace, degrees F in blue).

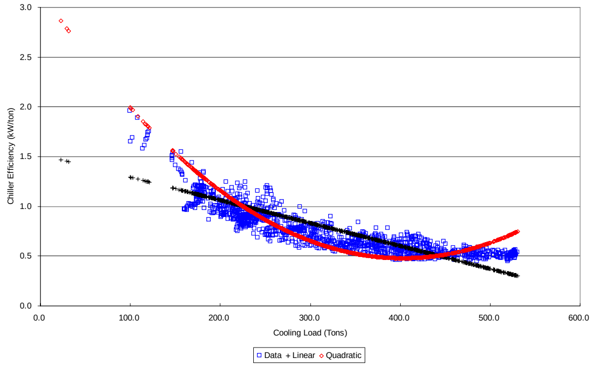

Figure 3: Example chiller analysis. Chiller performance plot of chiller efficiency (kW/ton) versus the chiller cooling load. Comparisons of linear (R^2 = 34.3%) and quadratic (R^2 = 53.4.3%) chiller models are shown.

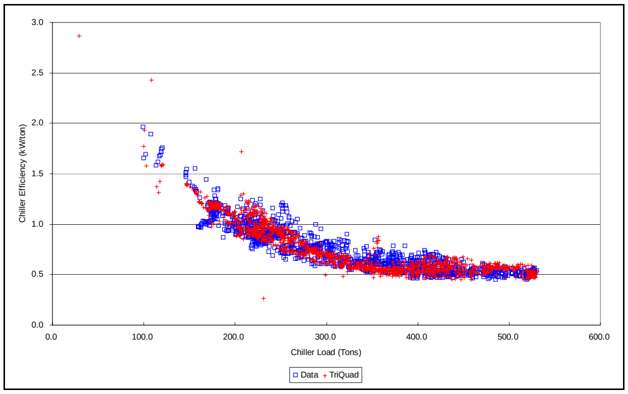

Figure 4: Example chiller analysis. Chiller performance plot of chiller efficiency (kW/ton) versus the chiller cooling load. In this figure a tri-quadratic chiller model (R^2 = 83.7%) is shown.

2.1.1.2.3.5 Calculation of Annual Energy Use

Once the chiller performance has been determined, the annual energy use can be calculated using the simple or temperature dependent models to determine the power demand of the chiller at each bin of the cooling load distribution. For chillers with varying temperatures, a load frequency distribution, which contains the two water temperatures, provides the operating hours of the chiller at each bin level. The energy use E_i, and power level P_i are given by the equations below. The total annual energy use is then the sum of the product of the number of hours in each bin times the chiller power associated with that bin. Savings are then calculated by comparing the annual energy use of the baseline with the annual energy use of the post-retrofit period.

$$E_i = T_i * P_i$$

$$P_i = (1 / Eff_i) * (Q_{evap,i})$$

$$E_{annual} = \sum_i \left(T_i * P_i\right)$$

where:

i = bin index, as defined by load frequency distribution
T_i = number of hours in bin i
P_i = equipment power use at load bin i
Eff_i = chiller 1/COP in bin i
$Q_{evap,i}$ = chiller load in bin i

2.1.1.2.4 Boilers and Furnaces

In-situ boiler and furnace performance measurements, for non-reheat boilers and furnaces, are listed in Appendix E of ASHRAE Guideline 14-2002. These procedures, which were obtained from the previously noted published literature on performance measurements of boilers and furnaces,[99,100,101,102,103,104,105] are grouped into four methods (i.e., single-point, single-point with manufacturer's data, multiple point with imposed loads, and multiple point tests using short term monitoring) that use three measurement techniques (i.e., direct method, direct heat loss method, and indirect combustion method), for a total of twelve methods.

The choice of method depends on boiler type (i.e., constant fire boiler, or variable-fire boilers) and availability of measurements (i.e., fuel meters, steam meters, etc.). For constant fire boilers, the boiler load is virtually constant. Therefore, a single measurement or series of measurements in a full load will characterize the boiler or furnace efficiency at a given set of ambient conditions. For variable fire boilers, the fuel use and output of the boiler varies. Therefore, the efficiency of the boiler will vary depending upon the load of the boiler as described by the manufacturer's efficiency curve.

Figure 5 shows an example of the measured performance of a variable-fire, low pressure steam boiler installed at an army base in Texas.[106]

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[99] Wei, G. 1997. op. cit.
[100] Dukelow, S.G. 1991. op. cit.
[101] Dyer, F.D., Maples, G. 1981. op. cit.
[102] Garcia-Borras, T. 1983. op. cit.
[103] Aschner, F.S. 1977. op. cit.
[104] ASME. 1974. op. cit.
[105] Babcock and Wilcox. 1992. op. cit.
[106] Haberl, J., Lynn, B., Underwood, D., Reasoner, J., Rury, K. 2003. op. cit.

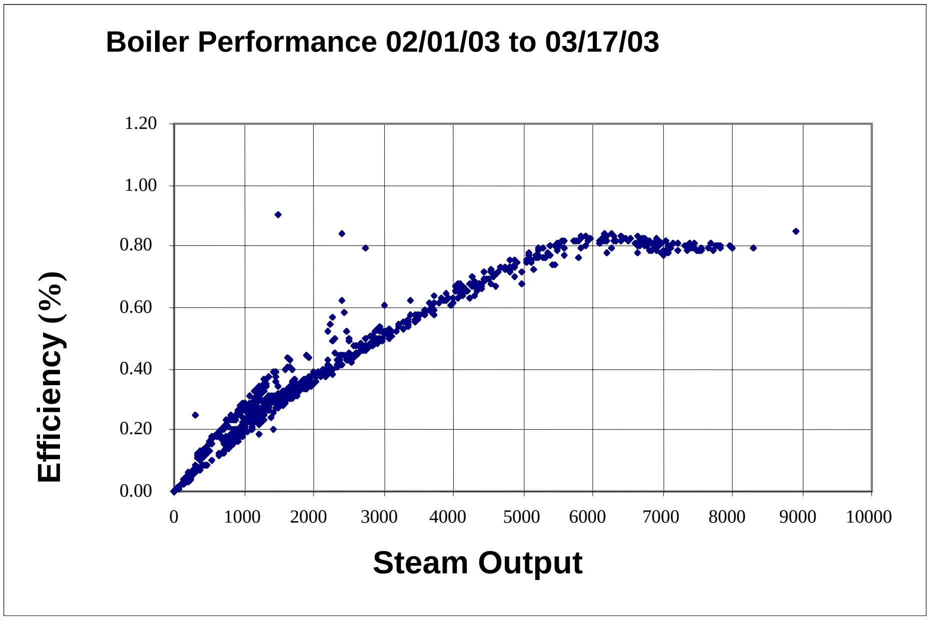

Figure 5: Example Boiler Performance Curve From Short Term Monitoring.[107]

2.1.1.2.4.1 Boiler efficiency measurements

There are three principal methods for determining boiler efficiency, the direct method (i.e., Input-Output method), the direct heat loss method, also known as the indirect method, and the indirect combustion efficiency method. The first two are recognized by the American Society of Mechanical Engineers (ASME) and are mathematically equivalent. They give identical results if all the heat balance factors are considered and the boiler measurements performed without error. ASME has formed committees from members of the industry and developed the performance test codes[108] that detail procedures of determining boiler efficiency by the first two methods mentioned above. The accuracy of boiler performance calculations is dependent on the quantities measured and the method used to determine the efficiency. In the direct efficiency method, these quantities are directly related to the overall efficiency. For example, if the measured boiler efficiency is 80%, then an error of 1% in one of the quantities measured will result in a 0.8% error in the efficiency. Conversely, in the direct heat loss method, the measured parameters are related to the boiler losses. Therefore, for the same boiler which had 80% efficiency, a measurement error of 1% in any quantity affects the overall efficiency by only 0.2% (i.e., 1% of the measured losses of 20%). As a result, the direct heat loss method is inherently more accurate than the direct method for boilers. However, the direct heat loss method requires more measurement and calculations. In general, boiler efficiencies range from 75% to 95% for utility boilers, and for industrial and commercial boilers, the average efficiency ranges from 76% to 83% on gas, 78% to 89% on oil and 85% to 88% for coal.[109,110]

2.1.1.2.4.1.1 Direct method

The direct method (i.e., the input-output method) is the simplest method to determine boiler efficiency. In this method, the heat supplied to the boiler and the heat absorbed by the water in the boiler in a given time period are directly measured. Using the direct method, the efficiency of a non-reheat boiler is given by.[111]

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[107] Haberl et al. 2003. ibid.
[108] ASME. 1974. Power Test Codes (PTC) 4.1a, Steam Generating Units. New York: ASME.
[109] Stallard, G.S., Jonas, T.S. 1996. Power Plant Engineering: Combustion Processes. New York: Chapman & Hall.
[110] Payne, F.W. 1985. Efficient Boiler Operations Sourcebook. Atlanta, GA: The Fairmont Press.
[111] Wei, G. 1997. op. cit.

$$\eta_b = \frac{Q_a}{Q_i} \times 100$$

where:

Q_a = heat absorbed (Btu/hr) = $\sum m_o h_o - \sum m_i h_i$

$m_o h_o$ = mass flow-enthalpy products of working fluid streams leaving boiler envelope, including main steam, blowdown, soot blowing steam, etc.

$m_i h_i$ = mass flow-enthalpy products of working fluid streams entering boiler envelope, including feedwater, desuperheating sprays, etc.

Q_i = heat inputs (Btu/hr) = $V_{fuel} \times HHV + Q_c$

V_{fuel} = volumetric flow of fuel into boiler (SCF/hr)

HHV = fuel higher heating value (Btu/SCF), and

Q_c = heat credits (Btu/hr). Heat credits are defined as the heat added to the envelope of the steam generating unit other than the chemical heat in the fuel "as fired." These credits include quantities such as sensible heat in the fuel, the entering air and the atomizing steam. Other credits include heat from power conversion in the pulverizer or crusher, circulating pump, primary air fan and recirculating gas fan.

2.1.1.2.4.1.2 Direct heat loss method

In the direct heat loss method the boiler efficiency equals 100% minus the boiler losses. The direct heat loss method tends to be more accurate than the direct method because the direct heat loss method focuses on determining the heat lost from the boiler, rather than on the heat absorbed by the working fluid. The direct heat loss methods determine efficiency using the following.[112]

$$\eta_b = \frac{Q_a}{Q_i} \times 100 = \frac{Q_i - Q_{loss}}{Q_i} \times 100$$

$$= 100 - L_{df} - L_{fh} - L_{am} - L_{rad} - L_{conv} - L_{bd} - L_{inc} - L_{unacct}$$

where:

Q_{loss} = heat losses (Btu/hr),

L_{df} = dry flue gas heat loss (%),

L_{fh} = fuel hydrogen heat loss (%),

L_{am} = combustion air moisture heat loss (%),

L_{rad} = radiation heat loss (%),

L_{conv} = convection heat loss (%),

L_{inc} = incombusted fuel loss (%),

L_{bd} = blowdown heat loss (%),

L_{unacct} = unaccounted for heat losses (%).

Using this method, the flue gas loss (sensible and latent heat), radiation and convection loss, fuel loss due to incomplete combustion, and blowdown loss are accounted for. In most boilers the flue gas loss is the largest loss, which can be determined by a flue gas analysis. Flue gas losses vary with flue gas exit temperature, fuel composition and type of firing.[113] Radiation and convection loss can be obtained from the standard curves.[114] Unaccounted for heat losses can also be obtained from published industry sources,[115] which cite losses of 1.5% for solid fuels, and 1% for gaseous or liquid fuel boilers. Losses from boiler blowdown should also be measured. Typical values can be found in various sources.[116,117]

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[112] Wei, G. 1997. ibid.

[113] Aschner, F.S. 1977. op. cit.

[114] Babcock and Wilcox. 1992. op. cit.

[115] Dukelow, S.G. 1991. op. cit.

[116] Witte, L.C., Schmidt, P.S., Brown, D.R. 1988. Industrial Energy Management and Utilization. New York: Hemisphere Publishing Corporation.

[117] Aschner, F.S. 1977. op. cit.

2.1.1.2.4.1.3 Indirect combustion method

The indirect combustion method can also be used to measure boiler efficiency. The combustion efficiency is the measure of the fraction of fuel-air energy available during the combustion process, calculated from the following:[118,119]

$$\eta_c = \frac{\left|h_p\right| - \left|h_f + h_a\right|}{Q_i} \times 100$$

where:

η_c = combustion efficiency (%)
h_p = enthalpy of products (Btu/lb)
h_f = enthalpy of fuel (Btu/lb)
h_a = enthalpy of combustion air, Btu/lb
Q_i = heat inputs (Btu/hr) = $V_{fuel} \times HHV + Q_c$

Indirect combustion efficiency can be related to direct efficiency or direct heat loss efficiency measurements using the following:[120,121]

$$\eta_b = \eta_c - L_{rad} - L_{conv} - L_{unacct}$$

On the right side of the equation, the loss terms are usually small for well insulated boilers. These terms must be accounted for when boilers are poorly insulated, or operated poorly (i.e., excessive blowdown control, etc.).

Table 10 provides a summary of the performance measurement methods (i.e., single-point, single-point with manufacturer's data, multiple point with imposed loads, and multiple point tests using short term monitoring), which use three efficiency measurement techniques (i.e., direct method, direct heat loss method, and indirect combustion method) that are listed in Appendix E of ASHRAE Guideline 14-2002. For each method, the pertinent measurements are listed along with the steps that should be taken to calculate the efficiency of the boiler or furnace being measured.

METHOD	DESCRIPTION OF THE METHOD
Method #1a: Single Point Test (direct method)	Measure: i) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) ii) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), iii) heat inputs. Applications: Non-reheat boilers and furnaces. Steps: • Operate boiler at typical existing operating conditions for the system. • Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.). • Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater desuperheating sprays, etc.). • Measure heat inputs. • Calculate efficiency using the direct efficiency method. • Calculate boiler and efficiency characteristics.
Method #1b: Single Point Test (direct heat loss method)	Measure: i) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss & unaccounted for losses), ii) heat inputs. Applications: Non-reheat boilers and furnaces.

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[118] Thumann, A. 1988. Guide to Improving Efficiency of Combustion Systems. Lilburn, GA: The Fairmont Press.
[119] Wei, G. 1997. op. cit.
[120] Garcia-Borras, T. 1983. Manual for Improving Boiler and Furnace Performance. Houston, TX: Gulf Publishing Company.
[121] Wei, G. 1997. op. cit.

	Steps: • Operate boiler at typical existing operating conditions for the system. • Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss & unaccounted for losses). • Measure heat inputs. • Calculate efficiency using direct heat loss method. • Calculate boiler and efficiency characteristics.
Method #1c: Single Point Test (indirect combustion method)	Measure: i) enthalpy of all combustion products, ii) enthalpy of fuel, iii) enthalpy of combustion air, iv) heat inputs. Applications: Non-reheat boilers and furnaces. Steps: • Operate boiler at typical existing operating conditions for system. • Measure enthalpy of all combustion products, the enthalpy of the fuel, the enthalpy of combustion air. • Measure heat inputs. • Calculate efficiency using the indirect combustion method. • Calculate boiler and efficiency characteristics.
Method #2a: Single Point Test with Manufacturer's Data (direct method)	Measure: i) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) ii) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), iii) heat inputs. Applications: Non-reheat boilers and furnaces. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. Steps: • Operate boiler at typical existing operating conditions for the system. • Obtain manufacturer's boiler efficiency curve. • Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.). • Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater desuperheating sprays, etc.). • Measure heat inputs. • Calculate efficiency using the direct efficiency method for the single point and compare to manufacturer's curve. • Calculate boiler and efficiency characteristics.
Method #2b: Single Point Test with Manufacturer's Data (direct heat loss method)	Measure: i) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss & unaccounted for losses), ii) heat inputs. Applications: Non-reheat boilers and furnaces. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. If single point does not confirm manufacturer's curve within 5% another boiler efficiency method will need to be used. Steps: • Operate boiler at typical existing operating conditions for the system. • Obtain manufacturer's boiler efficiency curve. • Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss & unaccounted for losses). • Measure heat inputs. • Calculate efficiency using direct heat loss method for a single point and compare to manufacturer's curve. • Calculate boiler and efficiency characteristics.
Method #2c: Single Point Test with Manufacturer's Data (indirect combustion method)	Measure: i) enthalpy of all combustion products, ii) enthalpy of fuel, iii) enthalpy of combustion air, iv) heat inputs. Applications: Non-reheat boilers and furnaces. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. If single point does not confirm manufacturer's curve within 5% another boiler efficiency method will need to be used. Steps: • Operate boiler at typical existing operating conditions for system. • Obtain manufacturer's boiler efficiency curve. • Measure enthalpy of all combustion products, the enthalpy of the fuel, the enthalpy of combustion air. • Measure heat inputs. • Calculate efficiency using the indirect combustion method, compare to manf. curve. • Calculate boiler and efficiency characteristics.
Method #3a: Multiple Point Test with Imposed Loads (direct method)	Measure over a range of operating conditions: i) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) ii) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), iii) heat inputs. Different loads are imposed on the boiler and measurements repeated. Boiler operation is assumed to follow manufacturer's efficiency curve. Applications: Non-reheat boilers and furnaces.

	Steps: • Obtain manufacturer’s efficiency curves. • Operate boiler at a given load. • Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.). • Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater desuperheating sprays, etc.). • Measure heat inputs. • Calculate efficiency using the direct efficiency method. • Change load on boiler and repeat steps 2 through 6. • Calculate boiler and efficiency characteristics.
Method #3b: Multiple Point Test with Imposed Loads (direct heat loss method)	Measure over a range of operating conditions: i) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss & unaccounted for losses), ii) heat inputs. Different loads are imposed on the boiler and measurements repeated. Boiler operation is assumed to follow manufacturer’s efficiency curve. Applications: Non-reheat boilers and furnaces. Steps: • Obtain manufacturer’s boiler efficiency curve. • Operate boiler at a given load. • Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss & unaccounted for losses). • Measure heat inputs. • Calculate efficiency using direct heat loss method for a single point and compare to manufacturer’s curve. • Change load on boiler and repeat steps 2 through 5. • Calculate boiler and efficiency characteristics.
Method #3c: Multiple Point Test with Imposed Loads (indirect combustion method)	Measure over a range of operating conditions: i) enthalpy of all combustion products, ii) enthalpy of fuel, iii) enthalpy of combustion air, iv) heat inputs. Different loads are imposed on the boiler and measurements are repeated. Boiler operation is assumed to follow the manufacturer’s efficiency curve. Applications: Non-reheat boilers and furnaces. Steps: • Obtain manufacturer’s boiler efficiency curve. • Operate boiler at a given load. • Measure enthalpy of all combustion products, the enthalpy of the fuel, the enthalpy of combustion air. • Measure heat inputs. • Calculate efficiency using the indirect combustion method and compare to manufacturer’s curve. • Change load on boiler and repeat steps 2 through 5. • Calculate boiler and efficiency characteristics.
Method #4a: Multiple Point Test through Short Term Monitoring (direct method)	Monitor over a range of operating conditions: i) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) ii) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), iii) heat inputs. The range of boiler loads should cover the normally expected loads that the boiler will experience (low and high). Applications: Non-reheat boilers and furnaces. Steps: • Choose appropriate time period for test. • Monitor boiler operation and record data values for mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.), mass flow and enthalpy of fluid streams entering the boiler (feedwater desuperheating sprays, etc.), and heat inputs. • Calculate efficiency using the direct efficiency method. • Calculate boiler and efficiency characteristics.
Method #4b: Multiple Point Test through Short Term Monitoring (direct heat loss method)	Monitor over a range of operating conditions: i) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss & unaccounted for losses), ii) heat inputs. The range of boiler loads should cover the normally expected loads that the boiler will experience (low and high). Applications: Non-reheat boilers and furnaces. Steps: • Choose appropriate period for the test. • Monitor all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss & unaccounted for losses), and monitor heat inputs. • Calculate efficiency using direct heat loss method for a single point and compare to manufacturer’s curve. • Calculate boiler and efficiency characteristics.
Method #4c: Multiple Point Test through Short Term Monitoring (indirect combustion efficiency method)	Monitor over a range of operating conditions: i) enthalpy of all combustion products, ii) enthalpy of fuel, iii) enthalpy of combustion air, iv) heat inputs. The range of boiler loads should cover the normally expected loads that the boiler will experience (low and high). Applications: Non-reheat boilers and furnaces. Steps:

	• Choose appropriate time period for test. • Monitor: enthalpy of all combustion products, the enthalpy of the fuel, the enthalpy of combustion air, and monitor heat inputs. • Calculate efficiency using the indirect combustion method and compare to manufacturer's curve. • Calculate boiler and efficiency characteristics.

Table 10: Boiler and Furnace Performance Testing Methods From ASHRAE Guideline 14-2002.[122]

2.1.1.2.4.2 Calculation of Annual Energy Use

Once the boiler performance has been measured the annual energy use can be calculated using the following procedures, depending upon whether the system is a constant fire boiler or variable fire boiler. Savings are then calculated by comparing the annual energy use of the baseline with the annual energy use of the post-retrofit period.

2.1.1.2.4.2.1 Constant Fire Boilers

In constant fire boilers the method assumes the load and fuel use are constant when the boiler is operating. Therefore, the annual fuel input is simply the full-load operating hours of the boiler times the fuel input. The total annual energy use is given by:

$$E_{annual} = T * P$$

where:

T = annual operating hours under full load
P = equipment power use

2.1.1.2.4.2.2 Variable fire boilers

For variable fire boilers the output of the boiler and fuel input vary according to load. Hence a frequency distribution of the load is needed that provides the operating hours of the boiler at each bin level. *In-situ* testing is then used to determine the efficiency of the boiler or furnace for each bin. The total annual energy use for variable fire boilers is given by:

$$E_{annual} = \sum_i \left(T_i * P_i\right)$$

where:

i = bin index, as defined by load variable frequency distribution
T_i = number of hours in bin i
P_i = equipment fuel input (& efficiency) at load bin (i)

2.1.1.2.5 Lighting

One of the most common retrofits to commercial buildings is to replace inefficient T-12 fluorescents and magnetic ballasts with T-8 fluorescents and electronic ballasts. This type of retrofit saves electricity associated with the use of the more efficient lighting, and depending on system type, can reduce cooling energy use because of reduced internal loads from the removal of the inefficient lighting. In certain climates, depending on system type, this can also mean an increase in heating loads, which are required to offset the heat from the inefficient lighting. Previously published studies show the cooling interaction can increase savings by 10 to 20%. The increased heating requirements can reduce savings by 5 to 20%.[123] Therefore, where the costs can be justified, accurate measurement of total energy savings can involve before/after measurements of the lighting loads, cooling loads, and heating loads.

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[122] ASHRAE. 2002. op. cit., pp. 154-156, (Copied with permission).

[123] Bou-Saada, T., Haberl, J., Vajda, J., Harris, L. 1996. "Total Utility Savings from the 37,000 Fixture Lighting Retrofit to the USDOE Forrestal Building," Proceedings of the 1996 ACEEE Summer Study (August).

2.1.1.2.5.1 Lighting Methods

ASHRAE Guideline 14-2002 provides six measurement methods to account for the electricity and thermal savings, varying from methods that utilize sampled before/after measurements to methods that use sub-metered before-after lighting measurement with measurements of increases or decreases to the heating and cooling systems from the removal of the internal lighting load. In general, the calculation of savings from lighting retrofits involves ascertaining the wattage or power reduction associated with the new fixtures, which is then multiplied times the hours per day (i.e., lighting usage profiles) that the lights are used. The lighting usage profiles can be calculated based on appropriate estimates of use, measured at the electrical distribution panel, or sampled with lighting loggers. Figure 6 shows an example of weekday-weekend profiles calculated with ASHRAE's Diversity Factor Toolkit.[124]

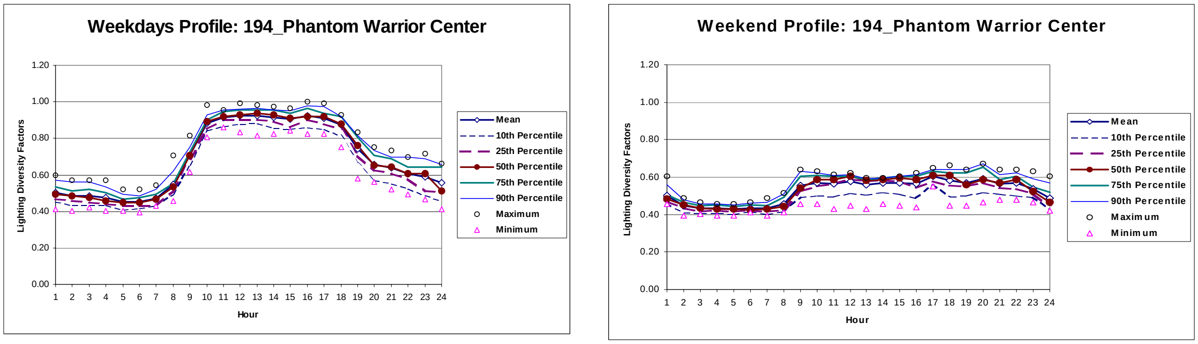

Figure 6: Example Weekday-Weekend Lighting Profiles.

Some lighting retrofits involve the installation of daylighting sensors to dim fixtures near the perimeter of the building or below skylights when lighting levels can be maintained with daylighting, thus reducing the electricity used for supplemental lighting. Measuring the savings from such daylighting retrofits usually involves before-after measurements of electrical power and lighting usage profiles.

Any lighting retrofit should include an assessment of the existing lighting levels, which is measured during daytime and nighttime conditions. All lighting retrofits should achieve and maintain lighting levels recommended by the Illuminating Engineering Society of North America (IESNA).[125] Any pre-retrofit lighting levels not maintaining IESNA lighting levels should be brought to the attention of the building owner or administrator. In the following section, the six methods, which are described in the ASHRAE Guideline 14-2002 are summarized. Table 11contains the lighting performance measurement methods from ASHRAE's Guideline 14-2002.

2.1.1.2.5.1.1 Method #1: Baseline and post-retrofit measured lighting power levels and stipulated diversity profiles.

In Method #1, before-after lighting power levels for a representative sample of lighting fixtures are measured using a Wattmeter, yielding an average Watt/fixture measurement for the pre-retrofit fixtures and post-retrofit fixtures. Lighting usage profiles are estimated or stipulated using the best available information, which represents the lighting usage profiles for the fixtures. This method works best for exterior lighting fixtures or lighting fixtures controlled by a timer or photocell. Lighting fixtures located in hallways, or any interior lighting fixtures that is operated 24 hours per day, 7 days per week or controlled by a timer is also suitable for this method. Savings benefits or penalties from thermal interactions are not included in this method.

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[124] Abushakra, B., Sreshthaputra, A., Haberl, J., Claridge, D. 2001. "Compilation of Diversity Factors and Schedules for Energy and Cooling Load Calculations – Final Report," submitted to ASHRAE under Research Project 1093-RP, Energy Systems Lab Report ESL-TR-01/04-01, Texas A&M University (April).

[125] IESNA. 2003. Lighting Handbook, 9th Edition, Illuminating Engineering Society of North America, New York, N.Y.

2.1.1.2.5.1.2 Method #2: Baseline and post-retrofit measured lighting power levels and sampled baseline and post-retrofit diversity profiles.

In Method #2, before-after lighting power levels for a representative sample of lighting fixtures are measured using a Wattmeter, yielding an average Watt/fixture measurement for the pre-retrofit fixtures and post-retrofit fixtures. Lighting usage profiles are measured with portable lighting loggers, or portable current meters attached to lighting circuits to determine the lighting usage profiles for the fixtures. This method is appropriate for any interior or exterior lighting circuit that has predictable usage profiles. Savings benefits or penalties from thermal interactions are not included in this method.

2.1.1.2.5.1.3 Method #3: Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit power levels with post-retrofit continuous diversity profile measurements.

In Method #3, pre-retrofit lighting power levels for a representative sample of lighting fixtures are measured using a Wattmeter, yielding an average Watt/fixture measurement for the pre-retrofit fixtures. Pre-retrofit lighting usage profiles are measured with portable lighting loggers, or portable current meters attached to lighting circuits to determine the lighting usage profiles for the fixtures. Post-retrofit lighting usage is measured continuously using either sub-metered lighting electricity measurements, or post-retrofit lighting power levels for a representative sample of lighting fixtures times a continuously measured diversity profile (i.e., using lighting loggers or current measurements on lighting circuits). This method is appropriate for any interior or exterior lighting circuit that has predictable usage profiles. Savings benefits or penalties from thermal interactions are not included in this method.

2.1.1.2.5.1.4 Method #4: Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit continuous sub-metered lighting.

In Method #4, pre-retrofit lighting power levels for a representative sample of lighting fixtures are measured using a Wattmeter, yielding an average Watt/fixture measurement for the pre-retrofit fixtures. Pre-retrofit lighting usage profiles are measured with portable lighting loggers, or portable current meters attached to lighting circuits to determine the lighting usage profiles for the fixtures. Post-retrofit lighting usage is measured continuously using sub-metered lighting electricity measurements. This method is appropriate for any interior or exterior lighting circuit that has predictable usage profiles. Savings benefits or penalties from thermal interactions are not included in this method.

2.1.1.2.5.1.5 Method #5: Includes methods #1, #2, or #3 with measured thermal effect (heating & cooling).

In Method #5, pre-retrofit and post-retrofit lighting electricity use is measured with Methods #1, #2, #3 or #4, and the thermal effect is measured using the component isolation method for the cooling or heating system. This method is appropriate for any interior lighting circuit that has predictable usage profiles. Savings benefits or penalties from thermal interactions are included in this method.

2.1.1.2.5.1.6 Method #6: Baseline and post-retrofit sub-metered lighting measurements and thermal measurements.

In Method #6, pre-retrofit and post-retrofit lighting electricity use is measured continuously using sub-metering, and the thermal effect is measured using whole-building cooling and heating sub-metered measurements. This method is appropriate for any interior lighting circuit. Savings benefits or penalties from thermal interactions are included in this method.

METHOD	DESCRIPTION OF THE METHOD
Method #1: Baseline and post-retrofit measured lighting power levels and stipulated diversity profiles.	Description: i) Obtain before-after lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures and the post-retrofit fixtures, ii) stipulate the lighting usage profiles using the best available information that represents lighting usage profiles for the facility. Application: Exterior lighting on a timer or photocell. Interior hallway lighting or any interior lighting used continuously or on a timer. Steps:

	• Obtain measured RMS watt/fixture data for pre-retrofit and post-retrofit fixtures. • Count the fixtures associated with each functional area in the building (e,g,, areas that have different usage profiles). • Define the lighting usage profiles for each functional area using the appropriate information that represents lighting usage profiles (e.g., continuously on, on during evening hours, etc.). • Calculate lighting energy usage characteristics.
Method #2: Before/after measured lighting power levels with sampled before/after diversity profiles.	Description: i) Measure lighting power levels using RMS watt meter for a sample of the pre-retrofit fixtures and the post-retrofit fixtures, ii) measure the lighting usage profiles using light loggers or portable metering attached to the lighting circuits. Application: Any exterior lighting or interior lighting with predictable usage profiles. Steps: • Measure watt/fixture using RMS watt meter for pre-retrofit and post-retrofit fixtures. • Count the fixtures associated with each functional area in the building (i.e., areas that have different usage profiles). • Sample lighting usage profiles for each functional area using lighting loggers and/or portable submetered RMS watt meters on lighting circuits. • Calculate lighting energy usage characteristics.
Method #3: Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit power levels with continuous diversity profile measurements.	Description: i) Obtain lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures and the post-retrofit fixtures, ii) sample the baseline lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits, iii) continuously measure the post-retrofit lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits. Application: Any exterior lighting or interior lighting. Steps: • Obtain lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures and the post-retrofit fixtures. • Sample the baseline lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits. • Continuously measure the post-retrofit lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits. • Calculate lighting energy usage characteristics.
Method #4: Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit continuous sub-metered lighting.	Description: i) Obtain lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures, ii) sample the baseline lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits, iii) continuously measure the post-retrofit lighting power usage using RMS watt measurements on submetered lighting circuits. Application: Any exterior lighting or interior lighting. Steps: • Obtain lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures. • Sample the baseline lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits. • Continuously measure the post-retrofit lighting usage using RMS watt measurements on submetered lighting circuits. • Calculate lighting energy usage characteristics.
Method #5: Method #1, #2, or #3 with stipulated thermal effects.	Description: i) Obtain lighting power profiles and usage using Method(s) #1, #2, #3, or #4 ii) Calculate the heating or cooling system efficiency using HVAC component isolation methods described in this document, iii) Calculate decrease in cooling load and increase in heating load. Application: Any interior lighting. Steps: • Obtain lighting power profiles and usage using Method(s) #1, #2, or #3, • Calculate the heating or cooling system efficiency using HVAC component isolation methods described in this document, • Calculate lighting energy usage characteristics. • Calculate decrease in cooling load and increase in heating load.
Method #6: Before/after sub-metered lighting and thermal measurements.	Description: i) Obtain lighting energy usage by measuring RMS lighting use continuously at the sub-metered level for pre-retrofit and post-retrofit conditions, ii) Obtain thermal energy use data by measuring sub-metered cooling or heating energy use for pre-retrofit and post-retrofit conditions, iii) develop representative lighting usage profiles from the sub-metered lighting data. Application: Any interior lighting projects. Any exterior lighting projects (no thermal interaction). Steps: • Obtain measured sub-metered lighting data for pre-retrofit and post-retrofit periods. • Develop representative lighting usage profiles from the sub-metered lighting data. • Calculate lighting energy usage characteristics. • Calculate decrease in cooling load and increase in heating load.

Table 11: Lighting Performance Measurement Methods From ASHRAE Guideline 14-2002.[126]

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[126] ASHRAE. 2002. op. cit., pp. 156-159, (Copied with permission).

2.1.1.2.5.2 Calculation of Annual Energy Use

The calculation of annual energy use varies according to lighting calculation method as shown in Table 12. The savings are determined by comparing the annual lighting energy use during the baseline period to the annual lighting energy use during the post-retrofit period. In Methods #5 and #6, the thermal energy effect can either be calculated using the component efficiency methods or it can be measured using whole-building, before-after cooling and heating measurements. Electric demand savings can be calculated using Methods #5 and #6 using diversity factor profiles from the pre-retrofit period and continuous measurement in the post-retrofit period. Peak electric demand reductions attributable to reduced chiller loads can be calculated using the component efficiency tests for the chillers. Savings are then calculated by comparing the annual energy use of the baseline with the annual energy use of the post-retrofit period.

TYPE OF MEASUREMENT	**PRE-RETROFIT ELECTRICITY USAGE CALCULATIONS**	**POST-RETROFIT ELECTRICITY USAGE CALCULATIONS**	**THERMAL ENERGY USAGE CALCULATIONS**
Method #1: Baseline and post-retrofit measured lighting power levels and stipulated diversity profiles.	For each lighting circuit: Annual energy use = (Power levels) x (24-hr *stipulated* profiles) x (number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) x (24-hr *stipulated* profiles) x (number of days assigned to each profile)	None.
Method #2: Before/after measured lighting power levels with sampled before/after diversity profiles.	For each lighting circuit: Annual energy use = (Power levels) x (24-hr *sampled* profiles) x (number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) x (24-hr *sampled* profiles) x (number of days assigned to each profile)	None.
Method #3: Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit power levels with continuous diversity profile measurements.	For each lighting circuit: Annual energy use = (Power levels) x (24-hr *sampled* profiles) x (number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) x (continuous diversity profile measurements)	None.
Method #4: Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit continuous sub-metered lighting.	For each lighting circuit: Annual energy use = (Power levels) x (24-hr *sampled* profiles) x (number of days assigned to each profile)	For each lighting circuit: Annual use = sub-metered lighting energy use.	None.
Method #5: Method #1, #2, #3, or #4 with calculated thermal effect.	Annual use = method #1, #2, #3, or #4 as appropriate.	Annual use = method #1, #2, #3, or #4 as appropriate.	Pre and post thermal load from the lighting is calculated using the component efficiency measurement methods for HVAC systems.
Method #6: Before/after sub-metered lighting and thermal measurements.	For each lighting circuit: Annual use = sub-metered lighting energy use.		Pre and post thermal load is calculated using before-after whole-building cooling and heating sub-metered measurements.

Table 12: Lighting Calculations Methods From ASHRAE Guideline 14-2002.[127]

2.1.1.2.6 HVAC Systems

As mentioned previously, during the 1950s and 1960s most engineering calculations were performed using slide rules, engineering tables and desktop calculators that could only add, subtract, multiply and divide. In the 1960s efforts were initiated to formulate and codify equations that could predict dynamic heating and cooling loads, including efforts to simulate HVAC systems. In 1965, ASHRAE recognized that there was a need to develop public-domain procedures for calculating the energy use of HVAC equipment and formed the Presidential Committee on Energy Consumption, which became the Task Group on Energy Requirements (TGER) for Heating and Cooling in 1969.[128] TGER commissioned two reports that detailed the public domain procedures for calculating the dynamic heat transfer through the building envelopes,[129] and procedures for

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[127] ASHRAE. 2002. op. cit., p. 160 (Copied with permission).

[128] Ayres, M., Stamper, E. 1995. op. cit.

[129] ASHRAE. 1969. Procedures for Determining Heating and Cooling Loads for Computerized Energy Calculations: Algorithms for Building Heat Transfer Sub-routines. M. Lokmanhekim, ed., American

simulating the performance and energy use of HVAC systems.[130] These procedures became the basis for today's public-domain building energy simulation programs such as BLAST, DOE-2, and EnergyPlus.[131,132] In addition, ASHRAE has produced several additional efforts to assist with the analysis of building energy use, including a modified bin method,[133] the HVAC01[134] and HVAC-02[135] toolkits, and HVAC simulation accuracy tests[136] which contain detailed algorithms and computer source code for simulating secondary and primary HVAC equipment. Studies have also demonstrated that properly calibrated simplified HVAC system models can be used for measuring the performance of commercial HVAC systems.[137,138,139,140]

2.1.1.2.6.1 HVAC System Types

In order to facilitate the description of measurement methods that are applicable to a wide range of HVAC systems, it is necessary to categorize HVAC systems into groups, such as single zone, steady state systems to the more complex systems such a multi-zone systems with simultaneous heating and cooling. To accomplish this, two layers of classification are proposed. In the first layer, systems are classified into two categories (Table 13): systems that provide heating or cooling under separate thermostatic control, and systems that provide heating and cooling under a combined control. In the second classification, systems are grouped according to: systems that provide constant heating rates, systems that provide varying heating rates, systems that provide constant cooling rates, and systems that provide varying cooling rates.

- HVAC systems that provide heating or cooling at a constant rate include: single zone, 2-pipe fan coil units, ventilating and heating units, window air conditioners, and evaporative cooling. Systems that provide heating or cooling at a constant rate can be measured using: single-point tests, multi-point tests, short-term monitoring techniques, or *in-situ* measurement combined with calibrated, simplified simulation.
- HVAC systems that provide heating or cooling at varying rates include: 2-pipe induction units, single zone with variable speed fan and/or compressors, variable speed ventilating and heating units, variable speed, and selected window air conditioners. Systems that provide heating or cooling at varying rates can be measured using: single-point tests, multi-point tests, short-term monitoring techniques, or short-term monitoring combined with calibrated, simplified simulation.
- HVAC systems that provide simultaneous heating and cooling include: multi-zone, dual duct constant volume dual duct variable volume, single duct constant volume w/reheat, single duct variable volume w/reheat, dual path systems (i.e., with main and preconditioning coils), 4-pipe fan coil units, and 4-pipe induction units. Such systems can be measured using: *in-situ* measurement combined with calibrated, simplified simulation.

Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA.

[130] ASHRAE. 1971. Procedures for Simulating the Performance of Components and Systems for Energy Calculations. Stoecker, W.F., ed., 2nd edition, American Society of Heating Refrigeration Air-conditioning Engineers, Atlanta, GA

[131] BLAST. 1993. BLAST Users Manual. BLAST Support Office, University of Illinois Urbana-Champaign.

[132] LBL. 1980, 1981, 1982, 1989. op. cit.

[133] Knebel, D.E. 1983. Simplified Energy Analysis Using the Modified Bin Method. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia.

[134] ASHRAE. 1999. op. cit.

[135] ASHRAE. 1993. op. cit.

[136] Yuill, G.K., Haberl, J.S. 2002. Development of Accuracy Tests for Mechanical System Simulation. Final Report for ASHRAE Research Project 865-RP, The University of Nebraska at Lincoln (July).

[137] Katipamula, S., Claridge, D.E., 1993. "Use of Simplified Systems Models to Measure Retrofit Savings," ASME Journal of Solar Energy Engineering, Vol. 115, pp. 57-68, May.

[138] Liu, M., Claridge, D.E. 1995. "Application of Calibrated HVAC System Models to Identify Component Malfunctions and to Optimize the Operation and Control Schedules," Solar Engineering 1995, ASME/JSME/JSES International Solar Energy Conference, Maui, Hawaii, March.

[139] Liu, M., Claridge, D.E. 1998. "Use of Calibrated HVAC System Models to Optimize System Operation," Journal of Solar Energy Engineering, May, Vol. 120.

[140] Liu, M., Wei, G., Claridge, D.E. 1998. "Calibrating AHU Models Using Whole Building Cooling and Heating Energy Consumption Data," Proceedings of 1998 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 3.

	HVAC System		
Test Method	**Constant Heating or Cooling**	**Variable Heating or Cooling**	**Simultaneous Heating and Cooling**
1. Single Point with Manufacturer’s Performance Data	✓		
2. Multiple Point with Manufacturer’s Performance Data.	✓	✓	
3. Multiple Point through Short Term Monitoring with Manufacturer’s Data.	✓	✓	
4. Short Term Monitoring and Calibrated, Simplified Simulation.	✓	✓	✓

Table 13: Relationship of HVAC Test Methods to Type of System.

2.1.1.2.6.2 HVAC System Testing Methods

In this section, four methods are described for the *in-situ* performance testing of HVAC systems as shown in Table 14, including: a single point method that uses manufacturer’s performance data, a multiple point method that includes manufacturer’s performance data, a multiple point that uses short-term data and manufacturer’s performance data, and a multiple point that uses short-term data and manufacturer’s performance data. Each of these methods is explained in the sections that follow.

2.1.1.2.6.2.1 Method #1: Single point with manufacturer’s performance data

In this method, the efficiency of the HVAC system is measured with a single-point (or a series) of field measurements at steady operating conditions. On-site measurements include: the energy input to system (e.g., electricity, natural gas, hot water or steam), the thermal output of system, and the temperature of surrounding environment. The efficiency is calculated as the measured output/input. This method can be used in the following constant systems: single zone systems, 2-pipe fan coil units, ventilating and heating units, single speed window air conditioners, and evaporative coolers.

2.1.1.2.6.2.2 Method #2: Multiple point with manufacturer’s performance data

In this method, the efficiency of the HVAC system is measured with multiple points on the manufacturer’s performance curve. On-site measurements include: the energy input to system (e.g., electricity, natural gas, hot water or steam), the thermal output of system, the system temperatures, and the temperature of surrounding environment. The efficiency is calculated as the measured output/input, which varies according to the manufacturer’s performance curve. This method can be used in the following systems: single zone (constant or varying), 2-pipe fan coil units, ventilating and heating units (constant or varying), window air conditioners (constant or varying), evaporative cooling (constant or varying) 2-pipe induction units (varying), single zone with variable speed fan and/or compressors, variable speed ventilating and heating units, and variable speed window air conditioners.

2.1.1.2.6.2.3 Method #3: Multiple point using short-term data and manufacturer’s performance data

In this method, the efficiency of the HVAC system is measured continuously over a short-term period, with data covering the manufacturer’s performance curve. On-site measurements include: the energy input to system (e.g., electricity, natural gas, hot water or steam), the thermal output of system, the system temperatures, and the temperature of surrounding environment. The efficiency is calculated as the measured output/input, which varies according to the manufacturer’s performance curve. This method can be used in the following systems: single zone (constant or varying), 2-pipe fan coil units, ventilating and heating units (constant or varying), window air conditioners (constant or varying), evaporative cooling (constant or varying), 2-pipe induction units (varying), single zone with variable speed fan and/or compressors, variable speed ventilating and heating units, and variable speed window air conditioners.

2.1.1.2.6.2.4 Method #4: Multiple point using short-term data and manufacturer's performance data

In this method, the efficiency of the HVAC system is measured continuously over a short-term period, with data covering the manufacturer's performance curve. On-site measurements include: the energy input to system (e.g., electricity, natural gas, hot water or steam), the thermal output of system, the system temperatures, and the temperature of surrounding environment. The efficiency is calculated using a calibrated air-side simulation of the system, which can include manufacturer's performance curves for various components. Similar measurements are repeated after the retrofit. This method can be used in the following systems: single zone (constant or varying), 2-pipe fan coil units, ventilating and heating units (constant or varying), window air conditioners (constant or varying), evaporative cooling (constant or varying), 2-pipe induction units (varying), single zone with variable speed fan and/or compressors, variable speed ventilating and heating units, variable speed window air conditioners, multi-zone, dual duct constant volume, dual duct variable volume, single duct constant volume w/reheat, single duct variable volume w/reheat, dual path systems (i.e., with main and preconditioning coils), 4-pipe fan coil units, and 4-pipe induction units.

METHOD	**DESCRIPTION OF THE METHOD**
Method #1: Single point with manufacturer's performance data	Measure: i) energy input to system (e.g., electricity, natural gas, hot water or steam), ii) thermal output of system, iii) temperature of surrounding environment (adjust for differences in efficiency with manufacturer's data). Applications: • single zone (constant mode) • 2-pipe fan coil units (constant mode) • ventilating and heating units, • single speed window air conditioners • evaporative coolers Steps: • Measure energy input to system (i.e, electricity, natural gas, hot water or steam). • Measure thermal output of system. • Measure temperature of space where system is operating. • Calculate efficiency as output/input. If efficiency does not agree to within 5% of manufacturer's performance data then use method #2, #3 or #4. • Adjust efficiency, using manufacturer's data if surrounding environmental conditions vary significantly over the year (i.e., ambient temperatures that the HVAC unit is exposed to). • Calculate savings by comparing differences in before-after component efficiency calculations applied to continuously measured post-retrofit thermal output energy requirements or sampled thermal load profiles.
Method #2: Multiple point with manufacturer's performance data	Measure at multiple points: i) energy input to system (e.g., electricity, natural gas, hot water or steam), ii) thermal output of system, iii) temperature of surrounding environment (adjust for differences in efficiency with manufacturer's data). Applications: • single zone (constant or varying) • 2-pipe fan coil units • ventilating and heating units (constant or varying) • window air conditioners (constant or varying) • evaporative cooling (constant or varying) • 2-pipe induction units (varying) • single zone with variable speed fan and/or compressors • variable speed ventilating and heating units • variable speed window air conditioners Steps: • Measure energy input to system at multiple points (i.e., electricity, natural gas, hot water or steam). • Measure corresponding thermal output of system at multiple points. • Measure temperature of space where system is operating during all tests. • Calculate efficiency as output/input. If efficiency does not agree to within 5% of manufacturer's performance data then use method #3 or #4. • Adjust efficiency, using manufacturer's data if surrounding environmental conditions vary significantly over the year (i.e., ambient temperatures that the HVAC unit is exposed to). • Calculate savings by comparing differences in before-after component efficiency calculations applied to continuously measured post-retrofit thermal output energy requirements or sampled thermal load profiles.
Method #3: Multiple point using short-term data and manufacturer's performance data	Continuously measure over a short-term period: i) energy input to system (e.g., electricity, natural gas, hot water or steam), ii) thermal output of system, iii) temperature of surrounding environment (adjust for differences in efficiency with manufacturer's data). Applications: • single zone (constant or varying) • 2-pipe fan coil units • ventilating and heating units (constant or varying) • window air conditioners (constant or varying) • evaporative cooling (constant or varying)

	• 2-pipe induction units (varying) • single zone with variable speed fan and/or compressors • variable speed ventilating and heating units • variable speed window air conditioners Steps: • Continuously measure over a short-term period energy input to system (e.g., electricity, natural gas, hot water or steam). • Measure corresponding thermal output of system at multiple points. • Measure temperature of space where system is operating during all tests. • Calculate efficiency as output/input. If efficiency does not agree to within 5% of manufacturer's performance data then use method #4. • Adjust efficiency, using manufacturer's data if surrounding environmental conditions vary significantly over the year (i.e., ambient temperatures that the HVAC unit is exposed to). • Calculate savings by comparing differences in before-after component efficiency calculations applied to continuously measured post-retrofit thermal output energy requirements or sampled thermal load profiles.
Method #4: Multiple point using short-term data and manufacturer's performance data	Measure over a representative range: i) thermal and electric energy input to system (e.g., electricity, natural gas, hot water or steam), ii) thermal output of system, iii) temperature of surrounding environment (may be used to adjust for losses to space), iv) develop an air-side simulation model that is representative of the system (Knebel 1983), v) calibrate the air-side model to the measured data for both pre-retrofit and post-retrofit conditions. Applications: • single zone (constant or varying) • 2-pipe fan coil units • ventilating and heating units (constant or varying) • window air conditioners (constant or varying) • evaporative cooling (constant or varying) • 2-pipe induction units (varying) • single zone with variable speed fan and/or compressors • variable speed ventilating and heating units • variable speed window air conditioners • multi-zone • dual duct constant volume • dual duct variable volume • single duct constant volume w/reheat • single duct variable volume w/reheat • dual path systems (i.e., with main and preconditioning coils) • 4-pipe fan coil units • 4-pipe induction units Steps: • Measure thermal input to system over a representative range (e.g., electricity, natural gas, hot water or steam). • Measure thermal output of system. • Measure temperature of space where system is operating. • Measure important system operation characteristics (e.g., cooling coil setpoint, heating coil setpoint, mixture of outside air to returning air, etc.) • For systems using chilled water, calculate efficiency as output/input over a range of conditions representative of operating conditions. • For systems using direct expansion of refrigerant, calculate efficiency as output/input over a range of varying cooling supply temperatures and heat rejection supply temperatures (i.e., to capture the efficiency of the A/C unit over varying outside conditions). • Develop an airside simulation model that is representative of the system (Knebel 1983) and calibrate the air-side model to the measured data for both pre-retrofit and post-retrofit conditions. • Calculate savings by applying the calibrated simulation models for the baseline and post-retrofit system to continuously measured post-retrofit cooling requirements or sampled cooling load profiles.

Table 14: HVAC System Testing Methods.[141,142]

2.1.1.2.6.3 Calculation of Annual Energy Use

The calculation of annual energy use varies according to HVAC calculation method as shown in Table 15. The savings are determined by comparing the annual HVAC energy use and demand during the baseline period to the annual HVAC energy use and demand during the post-retrofit period.

TYPE OF MEASUREMENT	**PRE-RETROFIT ENERGY USAGE AND ELECTRIC DEMAND CALCULATIONS**	**POST-RETROFIT ENERGY USAGE AND ELECTRIC DEMAND CALCULATIONS**

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[141] Haberl, J., Claridge, D., Turner. D. 2000b. "Workshop on Energy Measurement, Verification and Analysis Technology," Energy Conservation Task Force, Federal Reserve Bank, Dallas, Texas (April).

[142] This table contains material adapted from proposed HVAC System Testing Methods for ASHRAE Guideline 14-2002, which were not included in the published ASHRAE Guideline 14-2002.

Method #1: Single point with manufacturer's performance data	For each HVAC system: Annual energy use = (Measured Energy Use) x (Full Load Runtime Hours) Monthly demand use = (Measured Peak Electric Demand Use for System) x (System on/off Status for Each Month)	For each HVAC system: Annual energy use = (Measured Energy Use) x (Full Load Runtime Hours) Monthly demand use = (Measured Peak Electric Demand Use for System) x (System on/off Status for Each Month)
Method #2: Multiple point with manufacturer's performance data	For each HVAC system: Annual energy use = (Measured Energy Use for Each Operating Point) x (Full Load Runtime Hours for Each Operating Point) Monthly demand use = (Measured Peak Electric Demand Use for System for Each Operating Point) x (Maximum Operating Point for Each Month)	For each HVAC system: Annual energy use = (Measured Energy Use for Each Operating Point) x (Full Load Runtime Hours for Each Operating Point) Monthly demand use = (Measured Peak Electric Demand Use for System for Each Operating Point) x (Maximum Operating Point for Each Month)
Method #3: Multiple point using short-term data and manufacturer's performance data	For each HVAC system: Annual energy use = (Measured Energy Use for Each Operating Point) x (Full Load Runtime Hours for Each Operating Point) Monthly demand use = (Measured Peak Electric Demand Use for System for Each Operating Point) x (Maximum Operating Point for Each Month)	For each HVAC system: Annual energy use = (Measured Energy Use for Each Operating Point) x (Full Load Runtime Hours for Each Operating Point) Monthly demand use = (Measured Peak Electric Demand Use for System for Each Operating Point) x (Maximum Operating Point for Each Month)
Method #4: Multiple point using short-term data and manufacturer's performance data	For each HVAC system: Annual energy use = (Simulated Energy Use Using Calibrated Air-side Model) x (Binned Weather Data) Monthly demand use = (Simulated Peak Electric Demand Use for System) x (Maximum Bin Temperature for Month)	For each HVAC system: Annual energy use = (Simulated Energy Use Using Calibrated Air-side Model) x (Binned Weather Data) Monthly demand use = (Simulated Peak Electric Demand Use for System) x (Maximum Bin Temperature for Month)

Table 15: HVAC Performance Measurement Methods From ASHRAE Guideline 14-2002.[143]

2.1.2 Whole-building or Main-meter Approach

2.1.2.1 Overview

The whole-building approach, also called the main-meter approach, includes procedures that measure the performance of retrofits for those projects where whole-building pre-retrofit and post-retrofit data are available to determine the savings, and where the savings are expected to be significant enough that the difference between pre-retrofit and post-retrofit usage can be measured using a whole-building approach. Whole-building methods can use monthly utility billing data (i.e., demand or usage), or continuous measurements of the whole-building energy use after the retrofit on a more detailed measurement level (weekly, daily or hourly). Sub-metering measurements can also be used to develop the whole-building models, providing that the measurements are available for the pre-retrofit and post-retrofit period, and that meter(s) measures that portion of the building where the retrofit was applied. Each sub-metered measurement then requires a separate model. Whole-building measurements can also be used on stored energy sources, such as oil or coal inventories. In such cases, the energy used during a period needs to be calculated (i.e., any deliveries during the period minus measured reductions in stored fuel).

In most cases, the energy use and/or electric demand are dependent on one or more independent variables. The most common independent variable is outdoor temperature, which affects the building's heating and cooling energy use. Other independent variables can also affect a building's energy use and peak electric demand,

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[143] Haberl et al. 2000b. op. cit.

including: the building's occupancy (i.e., often expressed as weekday or weekend models), parking or exterior lighting loads, special events (i.e., Friday night football games), etc.

2.1.2.2 Whole-building energy use models

Whole-building models usually involve the use of a regression model that relates the energy use and peak demand to one or more independent variables. The most widely accepted technique uses linear or change-point linear regression to correlate energy use or peak demand as the dependent variable with weather data and/or other independent variables. In most cases the whole-building model has the form:

$$E = C + B_1V_1 + B_2V_2 + B_3V_3 + \ldots$$

where:

$E =$ the energy use or demand estimated by the equation,
$C =$ a constant term in energy units/day or demand units/billing period,
$B_n =$ the regression coefficient of an independent variable V_n ,
$V_n =$ the independent driving variable.

In general, the procedure for using whole building energy use models involves creating a whole-building model, a number of different regression models for the particular building, and then comparing the results and selecting the best model using R^2 and CV(RMSE). Table 16 and Figure 7 contain models listed in ASHRAE's Guideline 14-2002, which include steady-state: constant or mean models, models adjusted for the days in the billing period, two parameter models, three parameter models or variable-based degree-day models, four parameter models, five parameter models, and multivariate models. All of these models can be calculated with ASHRAE Inverse Model Toolkit (IMT), which was developed from Research Project 1050-RP.[144]

The steady-state, linear, change-point linear, variable-based degree-day and multivariate inverse models contained in ASHRAE's IMT have advantages over other types of models. First, since the models are simple, and their use with a given dataset requires no human intervention, the application of the models can be on can be automated and applied to large numbers of buildings, such as those contained in utility databases. Such a procedure can assist a utility, or an owner of a large number of buildings, identify which buildings have abnormally high energy use. Second, several studies have shown that linear and change-point linear model coefficients have physical significance to operation of heating and cooling equipment that is controlled by a thermostat.[145,146,147,148] Finally, numerous studies have reported the successful use of these models on a variety of different buildings.[149,150,151,152,153,154]

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[144] Kissock et al. 2001. op. cit.

[145] Fels. 1986. op. cit.

[146] Rabl. 1988. op. cit.

[147] Rabl, Raihle. 1992. op. cit.

[148] Claridge et al. 1992. op. cit.

[149] Reddy, T.A., Haberl, J.S., Saman, N.F., Turner, W.D., Claridge, D.E., Chalifoux, A.T. 1997. "Baselining Methodology for Facility-Level Monthly Energy Use - Part 1: Theoretical Aspects," ASHRAE Transactions-Research, Vol. 103, Pt. 2, pp. 336-347 (June).

[150] Reddy, T.A., Haberl, J.S., Saman, N.F., Turner, W.D., Claridge, D.E., Chalifoux, A.T. 1997. "Baselining Methodology for Facility-Level Monthly Energy Use - Part 2: Application to Eight Army Installations," ASHRAE Transactions-Research, Vol. 103, Pt. 2, pp. 348-359 (June).

[151] Haberl, J., Thamilseran, S., Reddy, A., Claridge, D., O'Neal, D., Turner, D. 1998. "Baseline Calculations for Measuring and Verification of Energy and Demand Savings in a Revolving Loan Program in Texas," ASHRAE Transactions-Research, Vol. 104, Pt. 2, pp. 841-858 (June).

[152] Turner, D., Claridge, D., O'Neal, D., Haberl, J., Heffington, W., Taylor, D., Sifuentes, T. 2000. "Program Overview: The Texas LoanSTAR Program: 1989–1999, A 10-year Experience," Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 4, pp. 4.365–4.376 (August).

Steady-state models have disadvantages, including: an insensitivity to dynamic effects (e.g., thermal mass), insensitivity to variables other than temperature (e.g., humidity and solar), and inappropriateness for certain building types, i.e., buildings that have strong on/off schedule dependent loads or that display multiple change-points. If whole-building models are required in such applications, alternative models will need to be developed.

Name		**Independent Variable(s)**	**Form**	**Examples**
No Adjustment /Constant Model		None	$E = E_b$	Non weather sensitive demand
Day Adjusted Model		None	$E = E_b \text{ x } \frac{\text{day}_b}{\text{day}_c}$	Non weather sensitive use (fuel in summer, electricity in summer)
Two Parameter Model		Temperature	$E = C + B_1 (T)$	
Three Parameter Models		Degree days/Temperature	$E = C + B_1 (DD_{BT})$ $E = C + B_1 (B_2 - T)^+$ $E = C + B_1 (T - B_2)^+$	Seasonal weather sensitive use (fuel in winter, electricity in summer for cooling) Seasonal weather sensitive demand
Four Parameter, Change Point Model		Temperature	$E = C + B_1 (B_3 - T)^+ - B_2 (T - B_3)^+$ $E = C - B_1 (B_3 - T)^+ + B_2 (T - B_3)^+$	
Five Parameter Models		Degree days/Temperature	$E = C - B_1 (DD_{TH}) + B_2 (DD_{TC})$ $E = C + B_1 (B_3 - T)^+ + B_2 (T - B_4)^+$	Heating and cooling supplied by same meter.
Multi-Variate Models		Degree days/Temperature, other independent variables	Combination form	Energy use dependent non-temperature based variables (occupancy, production, etc.).

Table 16: Sample Models for the Whole-Building Approach from ASHRAE Guideline 14-2002.[155]

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[153] Haberl, J., Sreshthaputra, A., Claridge, D., Turner, D. 2001. "Measured Energy Indices for 27 Office Buildings," Proceedings of the 1st International Conference for Enhanced Building Operation, Austin, Texas, pp. 185-200 (July).

[154] Beasley, R., Haberl, J. 2002. "Development of a Methodology for Baselining the Energy Use of Large Multi-building Central Plants," ASHRAE Transactions-Research, Vol. 108, Pt. 1, pp. 251-259 (January).

[155] ASHRAE. 2002. op. cit. p. 25 (Copied with permission).

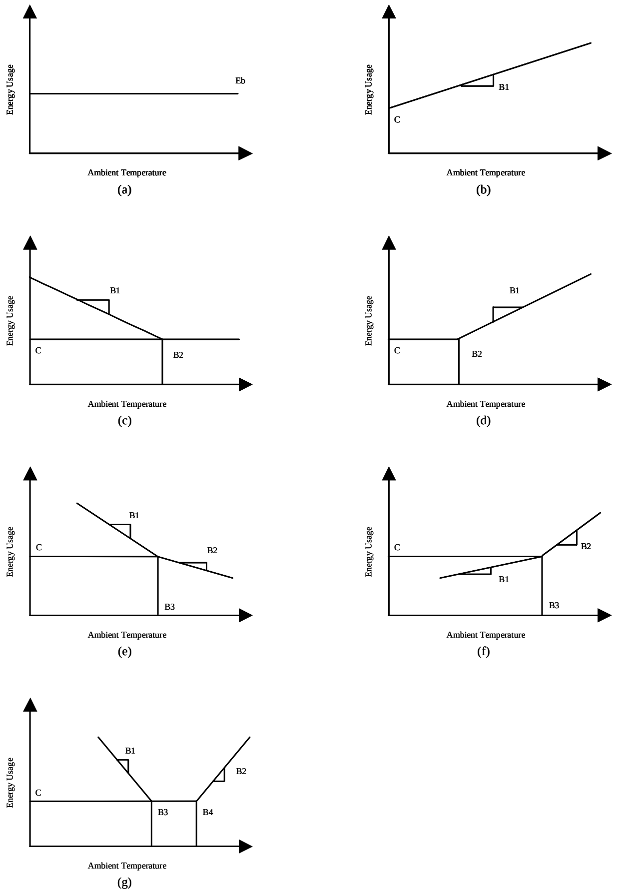

Figure 7: Sample Models for the Whole-building Approach. Included in this figure is: (a) mean or 1 parameter model, (b) 2 parameter model, (c) 3 parameter heating model (similar to a variable based degree-day model (VBDD) for heating), (d) 3 parameter cooling model (VBDD for cooling), (e) 4 parameter heating model, (f) 4 parameter cooling model, and (g) 5 parameter model.[156]

2.1.2.2.1 One-parameter or constant model

One-parameter, or constant models, are models where the energy use is constant over a given period. Such models are appropriate for modeling buildings that consume electricity in a way that is independent of the outside weather conditions. For example, such models are appropriate for modeling electricity use in buildings which are on district heating and cooling systems, since the electricity use can be well represented by a constant weekday-weekend model. Constant models are often used to model sub-metered data on lighting use that is controlled by a predictable schedule.

2.1.2.2.2 Day-adjusted Model

Day-adjusted models are similar to one-parameter constant models, with the exception that the final coefficient of the model is expressed as an energy use per day, which is then multiplied by the number of days in the billing period to adjust for variations in the utility billing cycle. Such day-adjusted models are often used with one, two, three, four and five parameter linear or change-point linear monthly utility models, where the energy use per period is divided by the days in the billing period before the linear or change-point linear regression is performed.

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[156] Haberl et al. 2000b. op. cit.

2.1.2.2.3 Two-parameter model

Two-parameter models are appropriate for modeling building heating or cooling energy use in extreme climates where a building is exposed to heating or cooling year-around, and the building has an HVAC system with constant controls that operates continuously. Examples include outside air pre-heating systems in artic conditions, or outside air pre-cooling systems in near-tropical climates. Dual-duct, single-fan, constant-volume systems, without economizers can also be modeled with two-parameter regression models. Constant use, domestic water heating loads can also be modeled with two-parameter models, which are based on the water supply temperature.

2.1.2.2.4 Three-parameter model

Three parameter models, which include change-point linear models or variable-based, degree day models, can be used on a wide range of building types, including residential heating and cooling loads, small commercial buildings, and models that describe the gas used by boiler thermal plants that serve one or more buildings. In Table 16, three parameter models have several formats, depending upon whether or not the model is a variable based degree-day model, or three-parameter, change-point linear models for heating or cooling. The variable-based degree day model is defined as:

$$E = C + B_1 (DD_{BT})$$

where:

C = the constant energy use below (or above) the change point, and
B_1 = the coefficient or slope that describes the linear dependency on degree-days,
DD_{BT} = the heating or cooling degree-days (or degree hours), which are based on the balance-point temperature.

The three-parameter change-point linear model for heating is described by:[157]

$$E = C + B_1 (B_2 - T)^+$$

where:

C = the constant energy use above the change point,
B_1 = the coefficient or slope that describes the linear dependency on temperature,
B_2 = the heating change point temperature,
T = the ambient temperature for the period corresponding to the energy use,
+ = positive values only inside the parenthesis.

The three-parameter change-point linear model for cooling is described by:

$$E = C + B_1 (T - B_2)^+$$

where:

C = the constant energy use below the change point,
B_1 = the coefficient or slope that describes the linear dependency on temperature,
B_2 = the cooling change point temperature,
T = the ambient temperature for the period corresponding to the energy use,
+ = positive values only for the parenthetical expression.

2.1.2.2.5 Four-parameter model.

The four-parameter change-point linear heating model is typically applicable to heating usage in buildings with HVAC systems that have variable-air volume, or whose output varies with the ambient temperature. Four-parameter models have also been shown to be useful for modeling the whole-building electricity use of grocery

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[157] Temperatures below zero are calculated as positive increases away from the change point temperature.

stores that have large refrigeration loads, and significant cooling loads during the cooling season. Two types of four-parameter models are listed in Table 16, including a heating model and a cooling model. The four parameter change-point linear heating model is given by:

$$E = C + B_1 (B_3 - T)^+ - B_2 (T - B_3)^+$$

where:

C = the energy use at the change point,
B_1 = the coefficient or slope that describes the linear dependency on temperature below the change point,
B_2= the coefficient or slope that describes the linear dependency on temperature above the change point
B_3= the change-point temperature,
T = the temperature for the period of interest,
+ = positive values only for the parenthetical expression.

The four parameter change-point linear cooling model is given by:

$$E = C - B_1 (B_3 - T)^+ + B_2 (T - B_3)^+$$

where:

C = the energy use at the change point,
B_1 = the coefficient or slope that describes the linear dependency on temperature below the change point,
B_2= the coefficient or slope that describes the linear dependency on temperature above the change point
B_3= the change-point temperature,
T = the temperature for the period of interest,
+ = positive values only for the parenthetical expression.

2.1.2.2.6 Five-parameter model

Five parameter change-point linear models are useful for modeling the whole-building energy use in buildings that contain air conditioning and electric heating. Such models are also useful for modeling the weather dependent performance of the electricity consumption of variable air volume air-handling units. The basic form for the weather dependency of either case is shown in Figure 7f, where there is an increase in electricity use below the change point associated with heating, an increase in the energy use above the change point associated with cooling, and constant energy use between the heating and cooling change points. Five parameter change-point linear models can be described using variable-based degree day models, or a five parameter model. The equation for describing the energy use with variable-based degree days is:

$$E = C - B_1 (DD_{TH}) + B_2 (DD_{TC})$$

where:

C = the constant energy use between the heating and cooling change points,
B_1 = the coefficient or slope that describes the linear dependency on heating degree-days,
B_2 = the coefficient or slope that describes the linear dependency on cooling degree-days,
DD_{TH} = the heating degree-days (or degree hours), which are based on the balance-point temperature.
DD_{TC} = the cooling degree-days (or degree hours), which are based on the balance-point temperature.

The five parameter change-point linear model that is based on temperature is:

$$E = C + B_1 (B_3 - T)^+ + B_2 (T - B_4)^+$$

where:

C = the energy use between the heating and cooling change points,

B_1 = the coefficient or slope that describes the linear dependency on temperature below the heating change point,
B_2= the coefficient or slope that describes the linear dependency on temperature above the cooling change point
B_3= the heating change-point temperature,
B_4= the cooling change-point temperature,
T = the temperature for the period of interest,
+ = positive values only for the parenthetical expression.

2.1.2.2.7 Whole-building Peak Demand Models

Whole-building peak electric demand models differ from whole-building energy use models in several respects. First, the models are not adjusted for the days in the billing period since the model is meant to represent the peak electric demand. Second, the models are usually analyzed against the maximum ambient temperature during the billing period. Models for whole-building peak electric demand can be classified according to weather-dependent and weather-independent models.

2.1.2.2.7.1 Weather-dependent, Whole-building Peak Demand Models

Weather-dependent, whole-building peak demand models can be used to model the peak electricity use of a facility. Such models can be calculated with linear and change-point linear models regressed against maximum temperatures for the billing period, or calculated with an inverse bin model.[158,159]

2.1.2.2.7.2 Weather-independent, Whole-building Peak Demand Models

Weather-independent, whole-building peak demand models are used to measure the peak electric use in buildings or sub-metered data that do not show significant weather dependencies. ASHRAE has developed a diversity factor toolkit for calculating weather-independent, whole-building peak demand models as part of Research Project 1093-RP. This toolkit calculates the 24-hour diversity factors using a quartile analysis. An example of the application of this approach is given in the following section.

2.1.2.3 Example: Whole-building energy use models

Figure 8 presents an example of the typical data requirements for a whole-building analysis, including one year of daily average ambient temperatures and twelve months of utility billing data. In this example of a residence, the daily average ambient temperatures were obtained from the National Weather Service (i.e., the average of the published min/max data), and the utility bill readings represent the actual readings from the customer's utility bill. To analyze these data several calculations need to be performed. First, the monthly electricity use (kWh/month) needs to be divided by the days in the billing period to obtain the average daily electricity use for that month (kWh/day). Second, the average daily temperatures need to be calculated from the published NWS min/max data. From these average daily temperatures the average billing period temperature need to be calculated for each monthly utility bill.

The data set containing average billing period temperatures and average daily electricity use is then analyzed with ASHRAE's Inverse Model Toolkit (IMT)[160] to determine a weather normalized consumption as shown in Figure 9 and Figure 10. In Figure 9, the twelve monthly utility bills (kWh/period) are shown plotted against the average billing period temperature along with a three-parameter change-point model calculated with the IMT. In Figure 10, the twelve monthly utility bills, which were adjusted for days in the billing period (i.e.,

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[158] Thamilseran, S., Haberl, J. 1995. "A Bin Method for Calculating Energy Conservation Retrofits Savings in Commercial Buildings," Proceedings of the 1995 ASME/JSME/JSES International Solar Energy Conference, Lahaina, Maui, Hawaii, pp. 111-124 (March).

[159] Thamilseran, S. 1999. "An Inverse Bin Methodology to Measure the Savings from Energy Conservation Retrofits in Commercial Buildings," Ph.D. Thesis, Mechanical Engineering Department, Texas A&M University (May).

[160] Kissock et al. 2001. op. cit.

kWh/day) are shown plotted against the average billing period temperature along with a three-parameter change-point model calculated with the IMT. In the analysis for this house, the use of an average daily model improved the accuracy of the unadjusted model (i.e., Figure 9) from an R^2 of 0.78 and CV(RMSE) of 24.0% to an R^2 of 0.83 and a CV(RMSE) of 19.5% for the adjusted model (i.e., Figure 10), which indicates a significant improvement in the model.

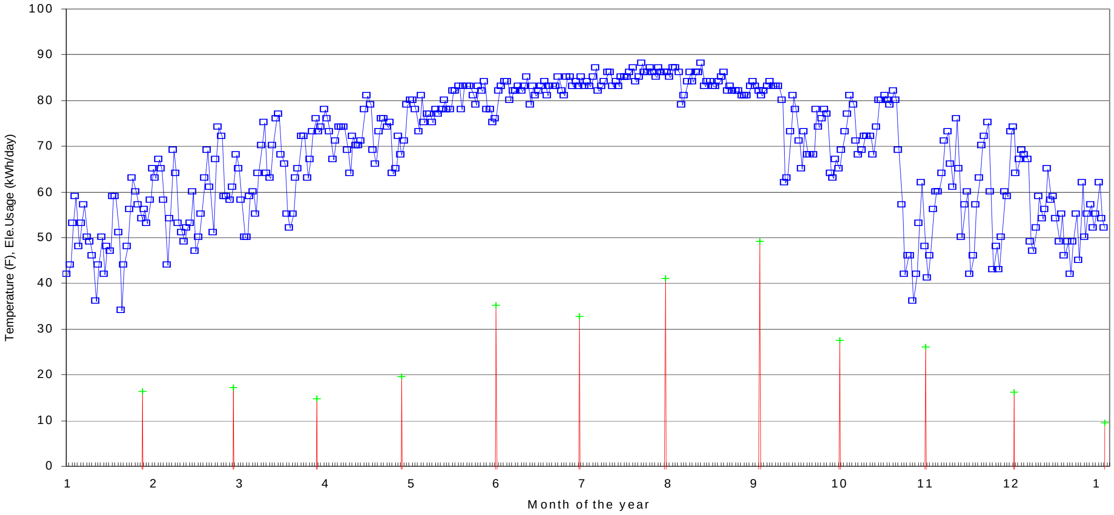

Figure 8: Example Data for Monthly Whole-building Analysis (upper trace, daily average temperature, F, lower points, monthly electricity use, kWh/day).

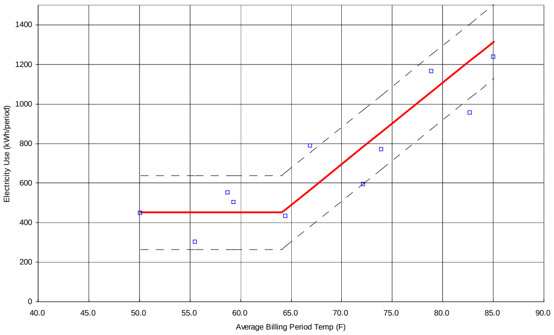

Figure 9: Example Unadjusted Monthly Whole-building Analysis (3P Model) for kWh/period (R^2 = 0.78, CV(RMSE) = 24.0%).

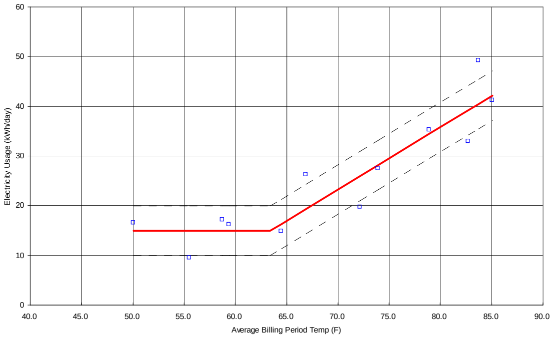

Figure 10: Example Adjusted Whole-building Analysis (3P Model) for kWh/day (R^2 = 0.83, CV(RMSE) = 19.5%).

In another example, the hourly steam use (Figure 11) and hourly electricity use (Figure 13) for the U.S.D.O.E. Forrestal Building is modeled with a daily weekday-weekend three parameter, change-point model for the steam use (Figure 12), and an hourly weekday-weekend demand model for the electricity use (Figure 14). To develop the weather-normalized model for the steam use the hourly steam data and hourly weather data were first converted into average daily data, then a three parameter, weekday-weekend model was calculated using the EModel software,[161] which contains similar algorithms as ASHRAE's IMT. The resultant model, which is shown in Figure 12, along with the daily steam, is well described with *an* R^2 *of* 0.87 *an* RMSE *of* 50,085.95 *kBtu/day and a* CV(RMSE) *of* 37.1%.

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[161] Kissock, J.K, Xun,W., Sparks, R., Claridge, D., Mahoney, J. Haberl, J. 1994. "EModel Version 1.4de," Texas A&M University, Energy Systems Laboratory, Department of Mechanical Engineering, Texas A&M University, December.

In Figure 14, hourly weather-independent 24-hour weekday-weekend profiles have been created for the whole-building electricity use using ASHRAE's 1093-RP Diversity Factor Toolkit.[162] These profiles can be used to calculate the baseline whole-building electricity use (i.e., using the mean hourly use) by multiplying times the expected weekdays and weekends in the year. The profiles can also be used to calculate the peak electricity use (i.e., using the 90th percentile).

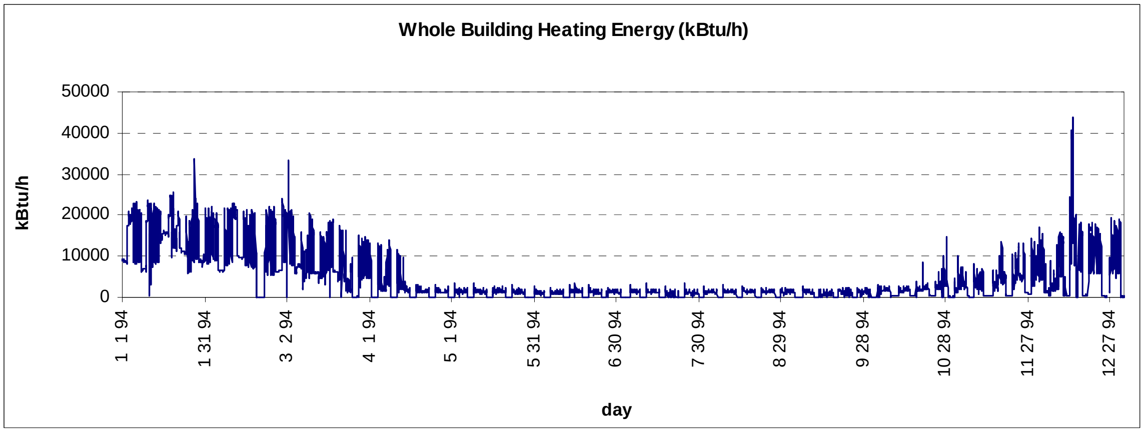

Figure 11: Example Heating Data for Daily Whole-building Analysis.

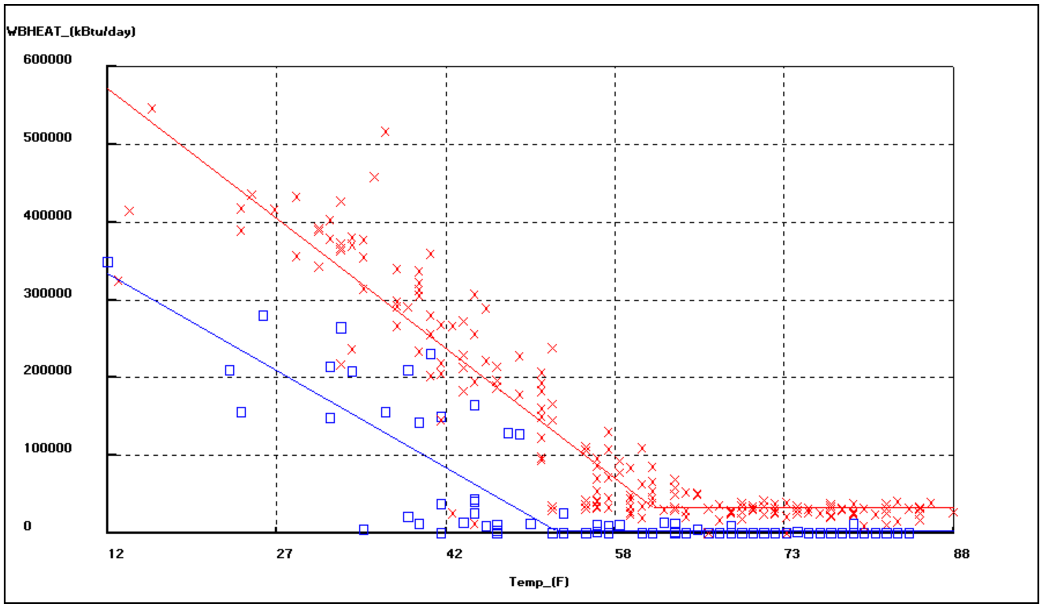

Figure 12: Example Daily Weekday-weekend Whole-building Analysis (3P Model) for Steam use (kBtu/day, R^2 = 0.87, RMSE = 50,085.95, CV(RMSE) = 37.1%). Weekday use (x), weekend use (□).

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[162] Abushakra et al. 2001. op. cit.

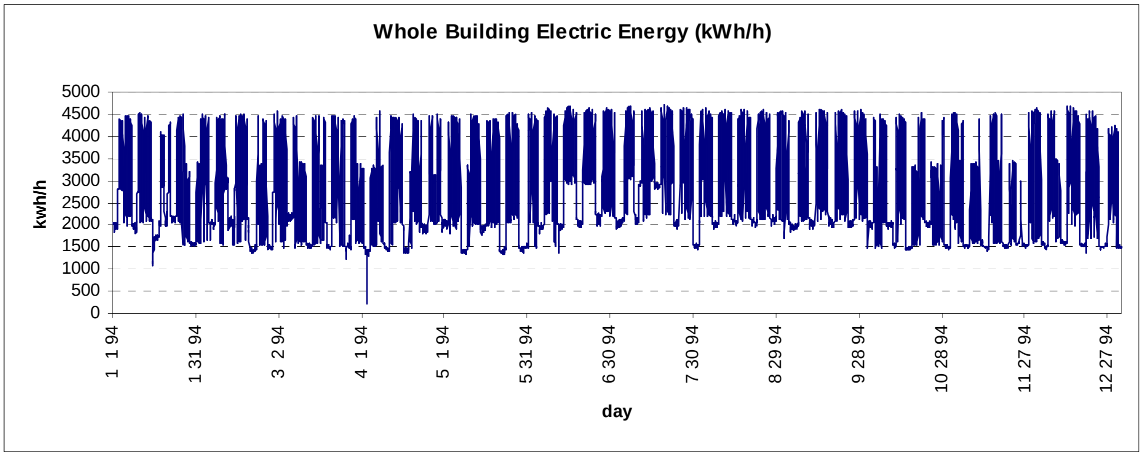

Figure 13: Example Electricity Data for Hourly Whole-building Demand Analysis.

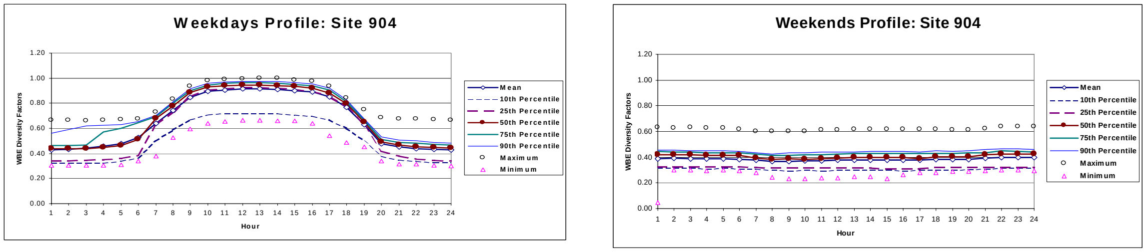

Figure 14: Example Weekday-weekend Hourly Whole-building Demand Analysis (1093-RP Model) for Electricity Use.

2.1.2.4 Calculation of Annual Energy Use

Once the appropriate whole-building model has been chosen and applied to the baseline data, the annual energy use for the baseline period and the post-retrofit period are then calculated. Savings are then calculated by comparing the annual energy use of the baseline with the annual energy use of the post-retrofit period.

2.1.3 Whole-building Calibrated Simulation Approach

Whole-building calibrated simulation normally requires the hourly simulation of an entire building, including the thermal envelope, interior and occupant loads, secondary HVAC systems (i.e., air handling units), and the primary HVAC systems (i.e., chillers, boilers). This is usually accomplished with a general purpose simulation program such as BLAST, DOE-2 or EnergyPlus, or similar proprietary programs. Such programs require an hourly weather input file for the location in which the building is being simulated. Calibrating the simulation refers to the process whereby selected outputs from the simulation are compared and eventually matched with measurements taken from an actual building. A number of papers in the literature have addressed techniques for accomplishing these calibrations, and include results from case study buildings where calibrated simulations have been developed for various purposes.[163,164,165,166,167,168,169,170,171,172,173,174,175,176,177,178]

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[163] Haberl, J., Bou-Saada, T. 1998. “Procedures for Calibrating Hourly Simulation Models to Measure Building Energy and Environmental Data,” ASME Journal of Solar Energy Engineering, Vol. 120, pp. 193-204 (August).

[164] Clarke, J.A, Strachan, P.A., Pernot, C. 1993. “An Approach to the Calibration of Building Energy Simulation Models,” ASHRAE Transactions, Vol. 99, Pt. 2, pp. 917-927.

[165] Diamond, S.C., Hunn, B.D. 1981. “Comparison of DOE-2 Computer Program Simulations to Metered Data for Seven Commercial Buildings,” ASHRAE Transactions, Vol. 87, Pt. 1, pp. 1222-1231.

2.1.3.1 Applications of Calibrated Whole-building Simulation

Calibrated whole-building simulation can be a useful approach for measuring the savings from energy conservation retrofits to buildings. However, it is generally more expensive than other methods; therefore, it is best reserved for applications where other, less costly approaches cannot be used. For example, calibrated simulation is useful in projects where either pre-retrofit or post-retrofit whole-building metered electrical data are not available (i.e., new buildings or buildings without meters such as many college campuses with central facilities). Calibrated simulation is desired in projects where there are significant interactions between retrofits, for example lighting retrofits combined with changes to HVAC systems, or chiller retrofits. In such cases the whole-building simulation program can account for the interactions, and in certain cases, actually isolate interactions to allow for end-use energy allocations. It is useful in projects where there are significant changes in the facility's energy use during or after a retrofit has been installed, where it may be necessary to account for additions to a building that add or subtract thermal loads from the HVAC system. In other cases, demand may change over time, where the changes are not related to the energy conservation measures. Therefore, adjustments to account for these changes will also be needed. Finally, in many newer buildings, as-built design simulations are being delivered as a part of the building's final documents. In cases where such simulations are properly documented they can be calibrated to the baseline conditions and then used to calculate and measure retrofit savings.

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[166] Haberl, J., Bronson, D., Hinchey, S., O'Neal, D. 1993. "Graphical Tools to Help Calibrate the DOE-2 Simulation Program to Non-weather Dependent Measured Loads," ASHRAE Journal, Vol. 35, No.1, pp. 27-32 (January).

[167] Haberl, J., Bronson, D., O'Neal, D. 1995. "An Evaluation of the Impact of Using Measured Weather Data Versus TMY Weather Data in a DOE-2 Simulation of an Existing Building in Central Texas," ASHRAE Transactions, Technical Paper No. 3921, Vol. 101, Pt. 2 (June).

[168] Hinchey, S.B. 1991. "Influence of Thermal Zone Assumptions on DOE-2 Energy Use Estimations of a Commercial Building," M.S. Thesis, Energy Systems Report No. ESL-TH-91/09-06, Texas A&M University.

[169] Hsieh, E.S. 1988. "Calibrated Computer Models of Commercial Buildings and Their Role in Building Design and Operation," M.S. Thesis, PU/CEES Report No. 230, Princeton University, Princeton, NJ.

[170] Hunn, B.D., Banks, J.A., Reddy, S.N. 1992. Energy Analysis of the Texas Capitol Restoration. The DOE-2 User News. 13(4): 2-10.

[171] Kaplan, M.B., Jones, B., Jansen, J. 1990a. "DOE-2.1C Model Calibration with Monitored End-use Data," Proceedings from the ACEEE 1990 Summer Study on Energy Efficiency in Buildings, Vol. 10, pp. 10.115-10.125.

[172] Kaplan, M.B., Caner, P., Vincent, G.W. 1992. "Guidelines for Energy Simulation of Commercial Buildings," Proceedings from the ACEEE 1992 Summer Study on Energy Efficiency in Buildings, Vol. 1, pp. 1.137-1.147.

[173] Katipamula, S., Claridge, D.E. 1993. "Use of Simplified Systems Models to Measure Retrofit Savings," ASME Journal of Solar Energy Engineering, Vol. 115, pp. 57-68, May.

[174] Liu, M., Claridge, D.E. 1995. "Application of Calibrated HVAC System Models to Identify Component Malfunctions and to Optimize the Operation and Control Schedules," Solar Engineering 1995, ASME/JSME/JSES International Solar Energy Conference, Maui, Hawaii, March.

[175] Liu, M., Claridge, D.E. 1998. "Use of Calibrated HVAC System Models to Optimize System Operation," Journal of Solar Energy Engineering, May, Vol. 120.

[176] Liu, M., Wei, G., Claridge, D.E. 1998. "Calibrating AHU Models Using Whole Building Cooling and Heating Energy Consumption Data," Proceedings of 1998 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 3.

[177] Manke, J., Hittle, D., Hancock, C.E. 1996. "Calibrating Building Energy Analysis Models Using Short Term Test Data," Proceedings of the 1996 International ASME Solar Energy Conference, San Antonio, TX, p. 369.

[178] McLain, H.A., Leigh, S.B., MacDonald, J.M. 1993. Analysis of Savings Due to Multiple Energy Retrofits in a Large Office Building. Oak Ridge National Laboratory, ORNL Report No. ORNL/CON-363, Oak Ridge, TN.

Unfortunately, calibrated whole-building simulation is not useful in all buildings. For example, if a building cannot be readily simulated with available simulation programs, significant costs may be incurred in modifying a program or developing a new program to simulate only one building (e.g., atriums, underground buildings, buildings with complex HVAC systems that are not included in a simulation program's system library). Additional information about calibrated, whole-building simulation can be found in ASHRAE's Guideline 14-2002.

Figure 15 provides an example of the use of calibrated simulation to measure retrofit savings in a project where pre-retrofit measurements were not available. In this figure, both the before-after whole-building approach and the calibrated simulation approach are illustrated. On the left side of the figure the traditional whole-building, before-after approach is shown for a building that had a dual-duct, constant volume system (DDCV) replaced with a variable air volume (VAV) system. In such a case where baseline data are available, the energy use for the building is regressed against the coincident weather conditions to obtain the representative baseline regression coefficients. After the retrofit is installed, the energy savings are calculated by comparing the projected pre-retrofit energy use against the measured post-retrofit energy use, where the projected pre-retrofit energy use calculated with the regression model (or empirical model), which was determined with the facility's baseline DDCV data.

In cases where the baseline data are not available (i.e., the right side of the figure), a simulation of the building can be developed and calibrated to the post-retrofit conditions (i.e., the VAV system). Then, using the calibrated simulation program, the pre-retrofit energy use (i.e., DDCV system) can be calculated for conditions in the post-retrofit period, and the savings calculated by comparing the simulated pre-retrofit energy use against the measured post-retrofit energy use. In such a case, the calibrated post-retrofit simulation can also be used to fill-in any missing post-retrofit energy use, which is a common occurrence in projects that measure hourly energy and environmental conditions. The accuracy of the post-retrofit model depends on numerous factors.

2.1.3.2 Methodology for Calibrated Whole-building Simulation

Calibrated simulation requires a systematic approach that includes the development of the whole-building simulation model, collection of data from the building being retrofitted and the coincident weather data. The calibration process then involves the comparison of selected simulation outputs against measured data from the systems being simulated, and the adjustment of the simulation model to improve the comparison of the simulated output against the corresponding measurements. The choice of simulation program is a critical step in the process, which must balance the model appropriateness, algorithmic complexity, user expertise, and degree of accuracy against the resources available to perform the modeling.

Data collection from the building includes the collection of data from the baseline and post-retrofit periods, which can cover several years of time. Building data to be gathered includes such information as the building location, building geometry, materials characteristics, equipment nameplate data, operations schedules, temperature settings, and at a minimum whole-building utility billing data. If the budget allows, hourly whole-building energy use and environmental data can be gathered to improve the calibration process, which can be done over a short-term or long-term period.

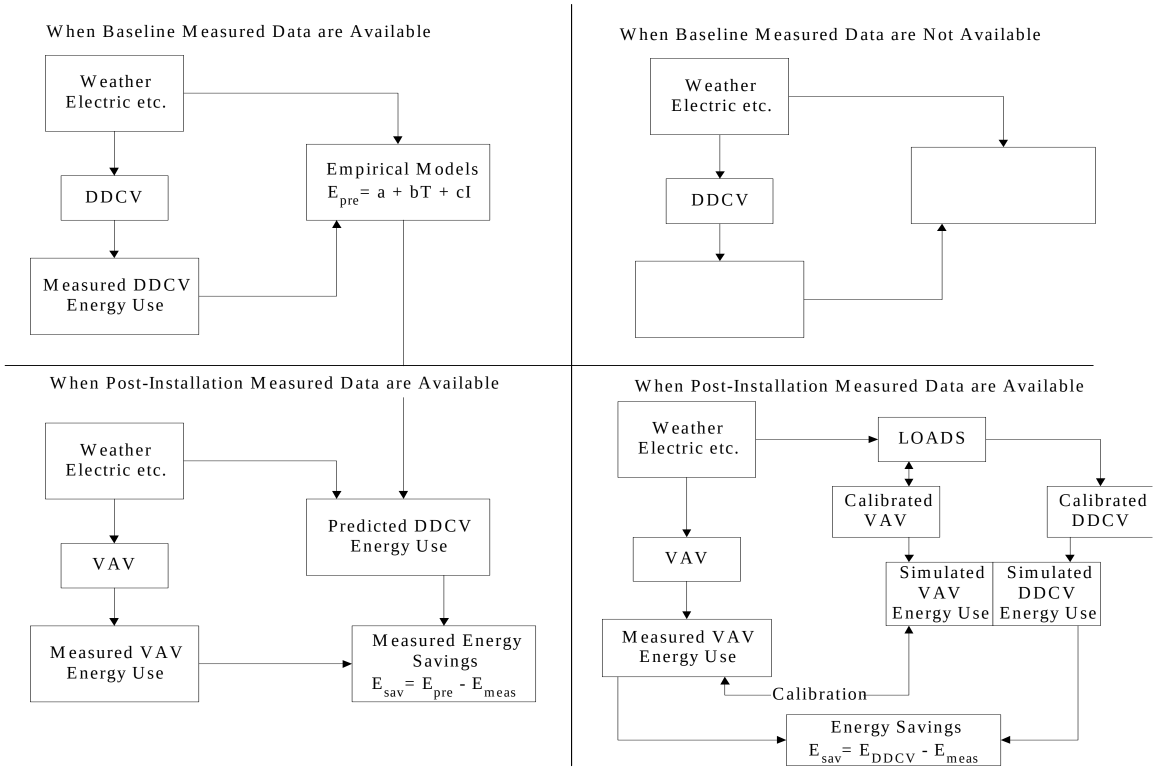

Figure 15: Flow Diagram for Calibrated Simulation Analysis of Air-Side HVAC System.[179]

Figure 16 provides an illustration of a calibration process that used hourly graphical and statistical comparisons of the simulated versus measured energy use and environmental conditions. In this example, the site-specific information was gathered and used to develop a simulation input file, including the use of measured weather data, which was then used by the DOE-2 program to simulate the case study building. Hourly data from the simulation program was then extracted and used in a series of special-purpose graphical plots to help guide the calibration process (i.e., time series, bin and 3-D plots). After changes were made to the input file, DOE-2 was then run again, and the output compared against the measured data for a specific period. This process was then repeated until the desired level of calibration was reached, at which point the simulation was proclaimed to be "calibrated." The calibrated model was then used to evaluate how the new building was performing compared to the design intent.

A number of different calibration tools have been reported by various investigators, ranging from simple X-Y scatter plots to more elaborate statistical plots and indices. Figure 17, Figure 18 and Figure 19 provide examples of several of these calibration tools. In Figure 17, an example of an architectural rendering tool is shown that assists the simulator with viewing the exact placement of surfaces in the building, as well as shading from nearby buildings, and north-south orientation. In Figure 18, temperature binned calibration plots are shown comparing the weather dependency of an hourly simulation against measured data. In this figure, the upper plots show the data as scatter plots against temperature. The lower plots are statistical, temperature-binned box-whisker-mean plots, which include the superpositioning of measured mean line onto the simulated mean line to facilitate a detailed evaluation. In Figure 19, comparative three-dimensional plots are shown that show measured data (top plot), simulated data (second plot from the top), simulated minus measured data (second plot from the bottom, and measured minus simulated data (bottom plot). In these plots, the day-of-the-year is the scale across the page (y axis), the hour-of-the-day is the scale projecting into the page (x axis), and the hourly electricity use is the vertical scale of the surface above the x-y plane. These plots are useful for determining how well the hourly schedules of the simulation match the schedules of the real building, and can be used to identify other certain schedule-related features. For example, in the front of plot (b) the saw-toothed feature is indicating on/off cycling of the HVAC system, which is not occurring in the actual building.

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[179] Haberl et al. 2000b. op. cit.

Table 17 contains a summary of the procedures used for developing a calibrated, whole-building simulation program, as defined in ASHRAE's Guideline 14-2002. In general, to develop a calibrated simulation, detailed information is required for a building, including information about the building's thermal envelope (i.e., the walls, windows, roof, etc.), information about the building's operation, including temperature settings, HVAC systems, and heating-cooling equipment that existed both during the baseline and post-retrofit period. This information is input into two simulation files, one for the baseline and one for the post-retrofit conditions. Savings are then calculated by comparing the two simulations of the same building, one that represents the baseline building, and one that represents the building's operations during the post-retrofit period.

STEP	**PROCEDURES**	**DATA OR INFORMATION REQUIRED**
Step 1: Calibrated Simulation Plan	• Develop Baseline Scenario • Develop Post-retrofit Scenario • Select simulation package • Select calibration tools	• Information about existing conditions, building location, surroundings, etc. • Information about post-retrofit conditions.
Step 2: Data Collection From Existing Building	• Visit site and collect data about baseline and post-retrofit conditions, characteristics, plans, • Collect energy use data, and information about building operations, and systems • Determine internal heat loads • Prepare data for input into simulation	• Utility billing data for baseline and for post-retrofit periods • Interval energy use and environmental data from building • Equipment schedules, thermostat settings, HVAC system types, performance measurements
Step 3: Data Input Into Simulation Program	• Develop whole-building simulation or building, including envelope, loads, systems, plant • Use architectural rendering to confirm inputs	• All building characteristics, system types, schedules, setpoints, etc., needed for developing simulation.
Step 4: Baseline Simulation Run and Comparison	• Run simulation. • Compare with measured data • Repeat process until simulation matches actual building	• All building characteristics, system types, schedules, setpoints, etc., needed for developing simulation. • On-sites measurements of energy and environmental data
Step 5: Post-retrofit Simulation Run and Comparison.	• Run simulation. • Compare with measured data • Repeat process until simulation matches actual building	• All building characteristics, system types, schedules, setpoints, etc., needed for developing simulation. • On-sites measurements of energy and environmental data
Step 6: Calculate Savings	• Compare baseline and post-retrofit simulations	
Step 7: Report findings	• Provide baseline & post-retrofit building descriptions. • Document building measurements • Include simulation plan • Present results • Provide input/output files from simulation	

Table 17: Calibrated, Whole-building Simulation Procedures from ASHRAE Guideline 14-2002.[180]

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[180] ASHRAE. 2002. op. cit. p. 35-43, (Copied with permission).

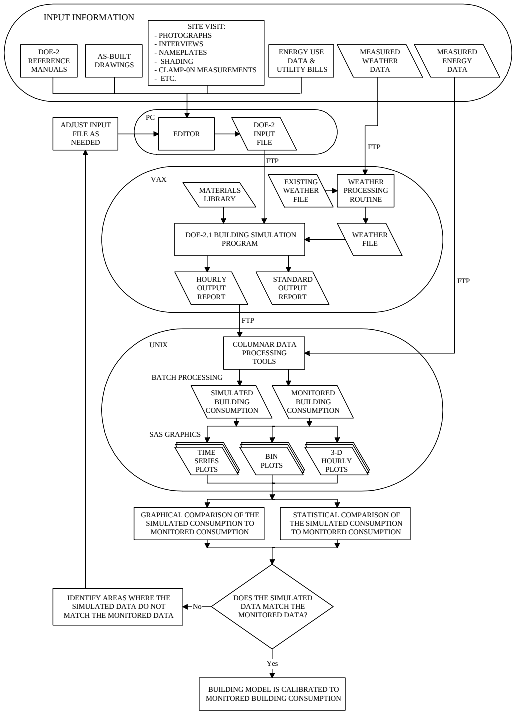

Figure 16: Calibration Flowchart. The sequence of processing routines that were used to develop graphical calibration procedures.[181]

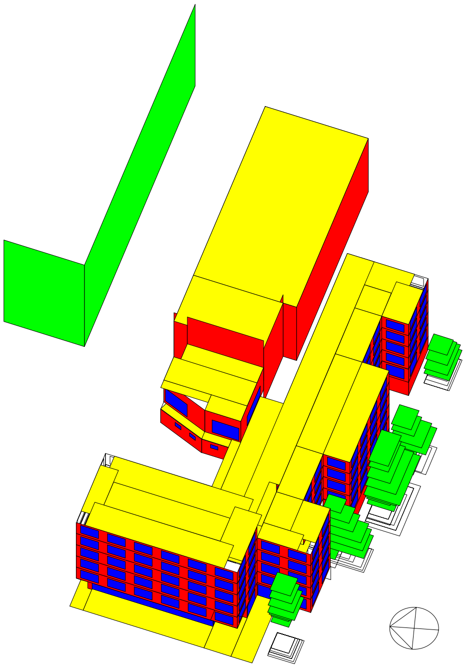

Figure 17: Example Architectural Rendering of the Robert E. Johnson Building, Austin, Texas.[182,183]

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[181] Bou-Saada, T. 1994. "An Improved Procedure for Developing A Calibrated Hourly Simulation Model of an Electrically Heated and Cooled Commercial Building," Master's Thesis, Mechanical Engineering Department, Texas A&M University (December), p. 54.

[182] Sylvester, K., Song, S., Haberl, J., Turner, D. 2002. "Case Study: Energy Savings Assessment for the Robert E. Johnson State Office Building in Austin, Texas," IBPSA Newsletter, Vol. 12, No. 2, pp. 22-28 (Summer).

[183] Huang & Associates. 1993. DrawBDL User's Guide. 6720 Potrero Ave., El Cerrito, California, 94530.

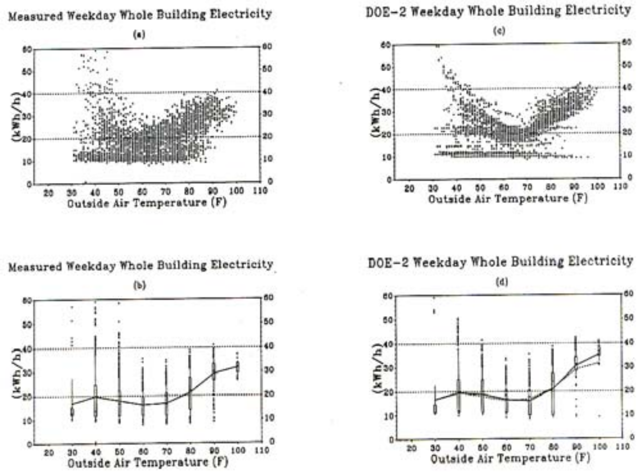

Figure 18: Temperature Bin Calibration Plots. Measured and simulated hourly weekday data as scatter plots against temperature in the upper plots and as statistical binned box -- whisker-mean plots in the lower plots.[184]

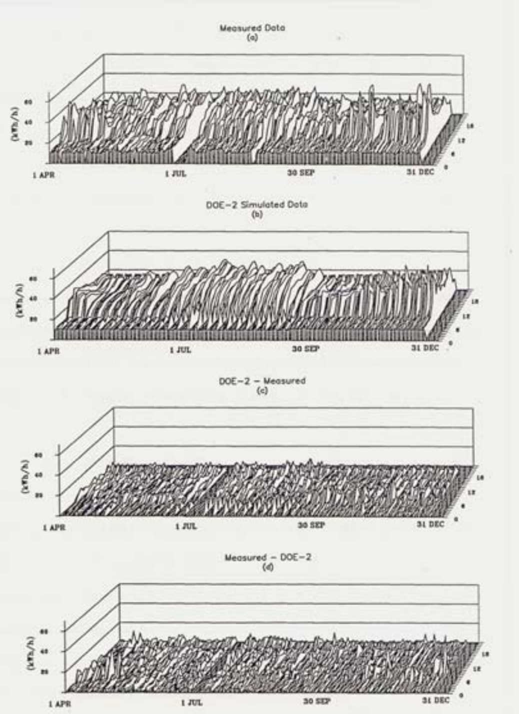

Figure 19: Comparative Three-dimensional Plots. (a) Measured Data. (b) Simulated Data. (c) Simulated-Measured Data. (d) Measured-Simulated Data.[185]

2.2 Role of M&V

Each Energy Conservation Measure (ECM) presents particular requirements. These can be grouped in functional sections as shown in Table 18. Unfortunately, in most projects, numerous variables exist so the assessments can be easily disputed. In general, the low risk (L) – reasonable payback ECMs exhibit steady performance characteristics that tend not to degrade or become easily noticed when savings degradation occurs. These include lighting, constant speed motors, two-speed motors and IR radiant heating. The high risk (H) – reasonable payback ECMs include Energy Management and Control Systems (EMCSs), variable speed drives and control retrofits. The savings from these ECMs can be overridden by building operators and not be noticed until years later. Most other ECMs fall in the category of “it depends.” The attention that the operations and maintenance directs at these dramatically impacts the sustainability of the operation and the savings. With an EMCS, operators can set up trend reports to measure and track occupancy schedule overrides, the various reset schedule overrides, variable speed drive controls and even monitor critical parameters which track mechanical systems performance. Table 18 illustrates a “most likely” range of ratings for the various categories.[186]

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[184] Bou-Saada, T. 1994. “An Improved Procedure for Developing A Calibrated Hourly Simulation Model of an Electrically Heated and Cooled Commercial Building,” Master’s Thesis, Mechanical Engineering Department, Texas A&M University (December), p.150.

[185] Bou-Saada, 1994. op. cit. p. 144.

[186] Culp, C. Hart, K.Q., Turner, B., Berry-Lewis, S. 2003. “Cost-Effective Measurement and Verification at Fairchild AFB, International Conference on Enhance Building Operation,” Energy Systems Laboratory Report, Texas A&M University (October).

	ECM			M&V		
ECM Strategies	Implement Cost	Payback	Savings	Implement Cost	Short Term Savings Risk	Long Term Savings Risk
Boiler Replace/Rebuild	M	M	M	H	M	H
Building Envelope Upgrades	H	L	M	H	L	M
Central Heating Plant Decentralization	VH	M	M		H	M
Chiller Plant Decentralization	VH	L	TBD			
Chiller Replace/Rebuild	H	L	M			
Constant Speed Motors	L	L	L		L	L
Cooling Tower Replace/Rebuild	H	L	M			
DDC Controls	M-H	M	H			
EMCS	H	L-M	H			
Ground Source HP	M	M	L-M			
HP Replace	L	M	L			
IR Radiant Heating	M-H	M	H			
Lighting	M	H	TBD			
Continuous Commissioning	H	VH	H			
Propane Air Plant	H	L-M				
Steam Traps	L	TBD				
Thermal Storage	H	L				
Tower Free Cooling	M-H	M				
Varaiable Speed Motors	L	H				
Very High	>$1M	<3 years	>$100K	>$100K	>15%/yr	>50%
High	>$100K	<5 years	>$10K	>$10K	>10%/yr	>35%
Medium	>$10K	<7 years	>$1K	>$1K	>5%/yr	>25%
Low	>$1K	> 8 years	<$1K	<$1K	<4%/yr	<10%

Table 18: Overview of Risks and Costs for ECMs.

Often, building envelopes or mechanical systems need to be replaced. Mechanical systems have finite lifetimes, ranging from two to five years for most light bulbs to 10 – 20+ years for chillers and boilers. Building envelop replacements, like insulation, siding, roof, windows and doors, can have lifetimes from 10 to 50 years. In these instances, life cycle costing should be done to compare the total cost of upgrading to more efficient technology. Also, the cost of M&V should be considered when determining how to sustain the savings and performance of the replacement. In many cases, the upgraded efficiency will have a payback of less than 10 years when compared to the current efficiency of the existing equipment. Current technology high efficiency upgrades normally use controls to acquire the high efficiency. These controls often connect to standard interfaces so that they communicate with today’s state of the art Energy Management and Control Systems (EMCSs).

2.3 Cost/Benefit Analysis

The target for work for the USAF has been 5% of the savings.[187] The cost of the M&V can exceed 5% if the risk of losing savings exceeds predefined limits. The Variable Speed Drive ECM illustrates these opportunities and risks. VSD equipment exhibits high reliability. Equipment type of failures normally happen when connection breaks occur with the control input, the remote sensor. Operator induced failures occur when the operator sets the unit to 100% speed and does not re-enable the control. Setting the unit to 100% can occur for legitimate reasons, including running a test, overriding a control program that does not provide adequate speed under specific, and typically unusual, circumstances, or requiring 100% operation for a limited time. The savings disappear if the VSD remains at 100% operating speed.

For example, consider a VSD ECM with ten (10) motors with each motor on a different air handling unit. Each motor has fifty (50) horsepower (HP). The base case measured these motors running 8,760 hours per year at full speed. Assume that the loads on the motors matched the nameplate 50 HP at peak loads. Although the actual load on an AHU fan varies with the state of the terminal boxes, assume that the load average equates to 80% of the full load since the duct pressure will rise as the terminal boxes reduce flow at the higher speed.

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[187] Culp et al. 2003. ibid.

Table 19 contains the remaining assumptions. To correctly determine the average power load, the average power must either be integrated over the period of consumption or the bin method must be used. For the purpose of this example, the 14.4% value will be used.

	Pre-ECM	Post-ECM	Comments
Hours / Yr	8760	8760	
$ / kWh	$0.06	$0.06	
$ / kW / month	$12.00	$12.00	
Average Speed	100%	50%	
PowerCurveExponent	2.8	2.8	Contains duct loss impact
Average Power Load	80%	14.4%	See Equation XXX
Total Motor HP	500	500	
Total kW	373	384	At full speed, ~3% loss in inverter

Table 19: VSD Example Assumptions

The equation below shows the relationship between the fan speed and the power consumed. The exponent has been observed to vary between 2.8 (at high flow) and 2.7 (at reduced flow) for most duct systems. This includes the loss term from pressure increases at a given fan speed. Changing the exponent from 2.8 to 2.7 reduces the savings by less than 5%.

$$\mathrm{Pwr} = \mathrm{Pwr}_0 \cdot \left(\frac{\%\mathrm{FullSpeed}}{\%\mathrm{FullSpeed}_0} \right)^{2.8}$$

Demand savings will not be considered in this example. Demand savings will likely be very low if the demand has a 13 month ratchet and the summer load requires some full speed operation during peak times. Assuming a $12.00/kW per month demand charge, demand savings could be high for off-season months if the demand billing resets monthly. Without a ratchet clause, rough estimates have yearly demand savings ranging up to $17,000 if the fan speed stays under 70% for 6 months per year. Yearly demand savings jump to over $20,000 if the fan speed stays under 60% for 6 months per year.

Figure 20 illustrates the savings expected from the VSD ECM by hours of use per year. The 5% and 10% of savings lines define the amount available for M&V expenditures at these levels. In this example, the ECM savings exceeds $253,000 per year. Five percent (5%) of savings over a 20 year project life makes $253K available for M&V and ten percent (10%) of the savings makes $506K available over the 20 year period. If the motors run less frequently than continuous, savings decrease as shown in Figure 20. Setting up the M&V program to monitor the VSDs on an hourly basis and report savings on a monthly report requires monitoring the VSD inverter with an EMCS to poll the data and create reports.

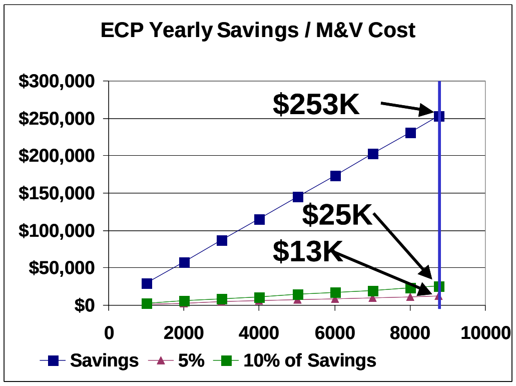

Figure 20: ECP Yearly Savings / M&V Cost.

To provide the impact of the potential losses from losing the savings, assume the savings degrades at a loss of 10% of the total yearly savings per year. Studies have shown that control of ECMs, like the VSD example, can expect to see 20% to 30% degradation in savings in 2 to 3 years. Figure 21 illustrates what happens to the savings in 20 years with 10% of the savings spent on M&V. Note that the losses exceed the M&V cost during the first year, resulting in a net loss of almost $3,000,000 over the 20 year period. Figure 22 shows the savings per year with a 10% loss of savings. M&V costs remain at 10% of savings. At the end of the 20 year period, the savings drop to almost $30,000 per year out of a potential savings of over $250,000 per year.

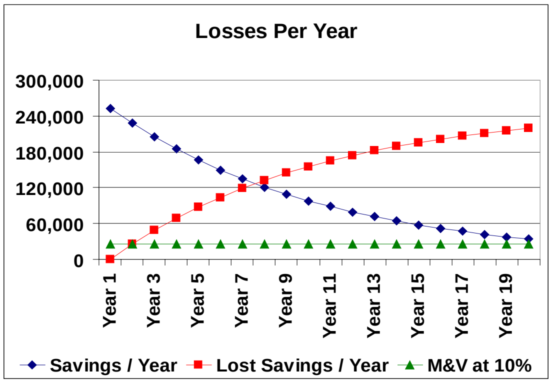

Figure 21: Yearly Impact of Ongoing Losses.

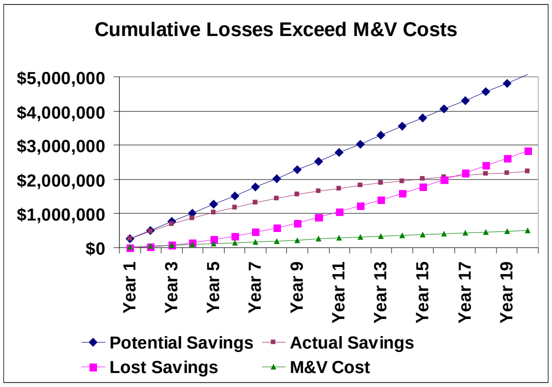

Figure 22: Cumulative Impact of Savings Loss.

This example shows the cumulative impact of losing savings on a year by year basis. The actual savings amounts will vary depending upon the specific factors in an ECM and can be scaled to reflect a specific application. Increasing the M&V cost to reduce the loss of savings often makes sense and must be carefully thought through.

2.4 Cost Reduction Strategies

M&V strategies can be cost reduced by lowering the requirements for M&V or by statistical sampling. Reducing requirements involves performing tradeoffs with the risks and benefits of having reliable numbers to determine the savings and the costs for these measurements.

2.4.1 Constant Load ECMs

Lighting ECMs can save 30% of the pre-ECM energy and have a payback in the range of 3 to 6 years. Assuming that the lighting ECM was designed and implemented per the specifications and the savings were verified to be occurring, just verifying that the storeroom has the correct ballasts and lamps may constitute acceptable M&V on a yearly basis. This costs far less than performing a yearly set of measurements, analyzing them and then creating reports. In this case, other safeguards should be implemented to assure that the bulb and ballast replacement occurs and meets the requirements specified.

High efficiency motor replacements provide another example of constant load ECMs. The key short term risks with motor replacements involve installing the right motor with all mechanical linkages and electrical components installed correctly. Once verified, the long term risks for maintaining savings occur when the motor fails. The replacement motor must be the correct motor or savings can be lost. A sampled inspection reduces this risk. Make sure to inspect all motors at least once every five (5) years.

2.4.2 Major Mechanical Systems

Boilers, chillers, air handler units, and cooling towers comprise the category of manor mechanical equipment in buildings. They need to be considered separately as each carries its own set of short-term and long-term risks. In general, measurements provide necessary risk reduction. The question becomes – what measurements reduce the risk of savings loss by an acceptable amount?

First, a risk assessment needs to be performed. The short-term risks for boilers involve installing the wrong size or installing the boiler improperly (not to specifications). Long-term savings sustainability risks tend to focus on the water side and the fire side. Water deposits (K^+, Ca^{++}, Mg^+) will form on the inside of the tubes and add a thermal barrier to the heat flow. The fire side can add a layer of soot if the O_2 level drops too low. Either of these reduces the efficiency of the boiler over the long haul. Generally this can take several years to impact the efficiency if regular tune-ups and water treatment occurs.

Boilers come in a wide variety of shapes and sizes. Boiler size can be used as a defining criteria for measurements. Assume that natural gas or other boiler fuels cost about $5.00 per MMBtu. Although fuel price constantly changes, it provides a reference point for this analysis. Thus a boiler with 1MMBtu per hour output, an efficiency of 80% and operating at 50% load 3500 hours per year, consumes about $11,000 per year. If this boiler replaced a less efficient boiler, say at 65%, then the net savings amounts to about $2,500 per year, assuming the same load from the building. At 5% of the savings, $125 per year can be used for M&V. This does not allow much M&V. At 10% of the annual savings, $250 per year can be used. At this level of cost, a combustion efficiency measurement could be performed, either yearly or bi-yearly, depending on the local costs. In 2003, the ASME's Power Test Code 4.1 (PTC-4.1)[188] was replaced with PTC4. Either of these codes allows two methods to measuring boiler efficiency. The first method uses the energy in equals energy out – using the first law of thermodynamics. This requires measuring the Btu input via the gas flow and the Btu output via the steam (or water) flow and temperatures. The second method measures the energy loss due to the content and temperature of the exhausted gases, radiated energy from the shell and piping and other loss terms (like blowdown). The energy loss method can be performed in less than a couple of hours. The technician performing these measurements must be skilled or significant errors will result in the calculated efficiency. The equation below shows the calculations required.

$$Efficiency = 100\% - Losses + Credits$$

The losses term includes the temperature of the exhaust gas and a measure of the unburned hydrocarbons by measuring CO_2 or O_2 levels, the loss due to excess CO and a radiated term. Credits seldom occur but could arise from solar heating the makeup water or similar contributions. The Greek letter "η" usually denotes efficiency.

As with boilers, a risk assessment needs to be performed. The short term risks for chillers involve sizing or improper installation. Long-term savings sustainability risks focus on the condenser water system, as circulation occurs in an open system. Water deposits (K^+, Ca^{++}, Mg^+, organics) will form on the inside of the condenser tubes and add a barrier to the thermal flow. These reduce the efficiency of the chiller over the long haul. Generally this can take several years to impact the efficiency if proper water treatment occurs. Depending on the environmental conditions, the quality of the makeup water and the water treatment, condenser tube fouling should be checked every year or at least every other year.

Chillers consume electricity in the case of most centrifugal, screw, scroll and reciprocating compressors. Absorbers and engine driven compressors use a petroleum based fuel. As with boilers, chiller size and application sets the basic energy consumption levels. Assume, for the purpose of this example, that electricity provides the chiller energy. Older chillers with water towers often operate at the 0.8 to 1.3 kW per ton level of efficiency. New chillers with water towers can operate in the 0.55 to 0.7 range of efficiency. Note that the efficiency of any chiller depends upon the specific operating conditions. Also assume the following: 500 tons centrifugal chiller with the specifications shown in Table 20. Under these conditions the chiller produces 400 tons of chilled water and requires an expenditure of $ 38,000 per year, considering both energy use and demand charges. Some utilities only charge demand charges on the transmission and delivery (T&D) parts of the rate structure. In that case, the cost at $0.06 / kWh would be closer to $28,000. Using the 5% (10%) guideline for M&V costs as a percentage of savings leaves almost $1,100 ($2,200) per year to spend on M&V. This creates an allowable expenditure over a 20 year project of $22,000 ($44,000) for M&V. If the utility has a ratchet clause in the rate structure, the amount for M&V increases to $1,700 ($3,400) per year. At $1,100 per year, tradeoffs will need to be made to stay within that "budget." The risks need to be weighed and decisions made as to what level of M&V costs will be allowed.

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[188] ASME. 1974. op. cit.

	No Rachet-4 Mo/Yr		13 Month Rachet		Comments
	Pre-ECM	Post-ECM	Pre-ECM	Post-ECM	
Hours / Yr	2000	2000	2000	2000	
Tons Cooling	400	400	400	400	
$ / kWh	$0.06	$0.06	$0.06	$0.06	
$ / kW / month	$12.00	$12.00	$12.00	$12.00	
Average Efficiency	0.90	0.57	0.90	0.57	kW / Ton
Yearly kWh	720000	456000	720000	456000	
Yearly kWh Cost	$43,200	$27,360	$43,200	$27,360	Energy use cost
Yearly kW Cost	$17,280	$10,944	$51,840	$32,832	Demand cost
Yearly Cost	$60,480	$38,304	$95,040	$60,192	Total
Savings		$22,176		$34,848	

Table 20: Example of Savings with a 500 Ton Chiller.

To determine the actual efficiency of a chiller requires accurate measurements of the chilled water flow, the difference between the chilled water supply and return temperatures and the electrical power provided to the chiller. Costs can be reduced using EMCS only if the temperature, flow and power sensors need to be installed.

Cooling tower replacement requires knowledge of the risks and costs involved. As with boilers and chillers, the primary risks involve the water treatment. Controls can be used to improve the efficiency of a chiller–tower combination by as much as 15% to 20%. As has been previously stated, control ECMs often get overridden and the savings disappear.

2.4.3 Control Systems

Control ECMs encompass a wide spectrum of capabilities and costs. Upgrading a pneumatic control system and installing EP (electronic to pneumatic) sensors involves the simple end. The complex side could span installing a complete EMCS with sophisticated controls, with various reset, pressurization and control strategies. Generally, EMCSs function as on/off controls and do not get widely used in sophisticated applications.

Savings due to EMCS controls bear high sustainability risks. When an operator overrides a strategy and forgets to re-enable it, the savings disappear. A common EMCS ECM requires the installation of equipment and programs used to set back temperatures or turn off equipment. Short-term risks involve setting up the controls so that performance enhances, or at least does not degrade, the comfort of the occupants. When discomfort occurs, either occupants set up “portable electric reheat units” or operators override the control program. For example, when the night set-back control does not get the space to comfort by occupancy, operators typically override instead of adjusting the parameters in the program. These actions tend to occur during peak loading times and then not get re-enabled during milder times. Long-term risks cover the same area as short-term risks. A new operator or a failure in remote equipment that does not get fixed will likely cause the loss of savings. Estimating the savings cost for various projects can be done when the specifics are known.

Risk abatement can be as simple as requiring a trend report weekly or at least monthly. M&V costs can generally be easily held under 5% when using an EMCS and creating trend reports.

2.5 M&V Sampling Strategies

M&V can be made significantly lower cost by sampling. Sampling also reduces the timeliness of obtaining specific data on specific equipment. The benefits of sampling arise when the population of items increases. Table 21 (M&V Guidelines: Measurement and Verification for Federal Energy Projects, Version 2.2, Appendix D) illustrates how confidence and precision impact the number of samples required in a given population of items.

Precision	20%	20%	10%
Confidence	80%	90%	90%
Population Size, N	Sample Size, n		
4	3	4	4
12	6	8	11
20	8	10	16
30	9	11	21
40	9	12	26
50	10	13	29
60	10	14	32
70	10	15	35
80	10	15	37
90	10	15	39
100	10	15	41
200	11	16	51
300	11	17	56
400	11	17	59
500	11	17	60
Infinite	11	17	68

Table 21: Sampling Requirements.

For example, lighting ECMs typically involve thousands of fixtures. To obtain a savings estimate with a confidence of 80% and a precision of 20%, 11 fixtures would need to be sampled. If the requirements increased to a confidence of 90% and a precision of 10%, 68 fixtures would need to be sampled.

The boiler ECM also represents opportunity for M&V cost reduction using sampling. Assume that the ECM included replacing 50 boilers. If a confidence of 80% and a precision of 20% satisfies the requirements, 10 boilers would need to be sampled. The cost is then reduced to 20% of the cost of measuring all boilers, a significant savings. A random sampling to select the sample set can easily be implemented.

In conclusion, since the persistence of savings has been shown to decrease with time, long-term M&V provides data to make these savings sustainable. Currently, a goal of about 5% of the savings per year has evolved as a preferred criteria for costing M&V, since the cost justification directly results from the savings obtained. Several general procedures have been discussed in this paper: using a monthly billing analysis, a daily or hourly procedure, a component isolation analysis, or a calibrated simulation. Each of these is applicable. The energy savings application and type of data available can be used to specify the optimal approach.