CHAPTER 40

BUILDING ENERGY MONITORING

BUILDING energy monitoring provides realistic and empirical information from field data to enhance understanding of actual building energy performance and can help quantify changes in performance over time. Although different building energy monitoring projects can have different objectives and scopes, all have several issues in common that allow methodologies and procedures (monitoring protocols) to be standardized.

This chapter provides guidelines for developing building monitoring projects that provide the necessary measured data at acceptable cost. The intended audience comprises building owners, building energy monitoring practitioners, and data end users such as energy and energy service suppliers, energy end users, building system designers, public and private research organizations, utility program managers and evaluators, equipment manufacturers, and officials who regulate residential and commercial building energy systems.

Monitoring projects can be **uninstrumented** (i.e., no additional instrumentation beyond the utility meter) or **instrumented** (i.e., billing data supplemented by additional sources, such as an installed instrumentation package, portable data loggers, or building automation system). Uninstrumented approaches are generally simpler and less costly, but they can be subject to more uncertainty in interpretation, especially when changes made to the building represent a small fraction of total energy use. It is important to determine (1) the accuracy needed to meet objectives, (2) the type of monitoring needed to provide this accuracy, and (3) whether the desired accuracy justifies the cost of an instrumented approach.

Instrumented field monitoring projects generally involve data acquisition systems (DASs), which typically comprise various sensors and data-recording devices (e.g., data loggers) or a suitably equipped building automation system. Projects may involve a single building or hundreds of buildings and may be carried out over periods ranging from weeks to years. Most monitoring projects involve the following activities:

- Project planning
- Site installation and calibration of data acquisition equipment (if required)
- Ongoing data collection and verification
- Data analysis and reporting

These activities often require support by several professional disciplines (e.g., engineering, data analysis, management) and construction trades (e.g., electricians, controls technicians, pipe fitters).

Useful building energy performance data cover whole buildings, lighting, HVAC equipment, water heating, meter readings, utility demand and load factors, excess capacity, controller actuation, and building and component lifetimes. Current monitoring practices vary considerably. For example, a utility load research project may tend to characterize the average performance of buildings with relatively few data points per building, whereas a test of new technology performance may involve monitoring hundreds of parameters within a single facility. Monitoring projects range from broad research studies to very specific, contractually required savings verification carried out by performance contractors. However, all practitioners should use accepted standards of monitoring practices to communicate results. Key elements in this process are (1) classifying the types of project monitoring and (2) developing consensus on the purposes, approaches, and problems associated with each type (Haberl et al. 1990; Misuriello 1987). For example, energy savings from energy service performance contracts can be specified on either a whole-building or component basis. The monitoring requirements for each approach vary widely and must be carefully matched to the specific project.

REASONS FOR ENERGY MONITORING

Monitoring projects can be broadly categorized by their goals, objectives, experimental approach, level of monitoring detail, and uses (Table 1). Other factors, such as resources available, data analysis procedures, duration and frequency of data collection, and instrumentation, are common to most, if not all, projects.

Energy End Use

Energy end-use projects typically focus on individual energy systems in a particular market sector or building type. Monitoring usually requires separate meters or data collection channels for each end use, and analysts must account for all factors that may affect energy use. Examples of this approach include detailed utility load research efforts, evaluation of utility incentive programs, and end-use calibration of computer simulations. Depending on the project objectives, the frequency of data collection may range from one-time measurements of full-load operation to continuous time-series measurements.

Specific Technology Assessment

Specific technology assessment projects monitor field performance of specific equipment or technologies that affect building energy use, such as envelope retrofit measures, major end-use system loads or savings from retrofits (e.g., lighting), or retrofits to or performance of mechanical equipment.

The typical goal of retrofit performance monitoring projects is to estimate savings resulting from the retrofit despite potentially significant variation in inside/outside conditions, building characteristics, and occupant behavior unrelated to the retrofit. The frequency and complexity of data collection depend on project objectives and site-specific conditions. Projects in this category assess variations in performance between different buildings or for the same building before and after the retrofit.

Field tests of end-use equipment are often characterized by detailed monitoring of all critical performance parameters and operational modes. In evaluating equipment performance or energy efficiency improvements, it is preferable to measure in situ performance. Although manufacturers' data and laboratory performance measurements can provide excellent data for sizing and selecting equipment, installed performance can vary significantly from that

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Table 1 Characteristics of Major Monitoring Project Types

Project Type	Goals and Objectives	General Approach	Level of Detail	Uses
Energy end use	Determine characteristics of specific energy end uses in building.	Often uses large, statistically designed sample. Monitor energy demand or use profile of each end use of interest.	Detailed data on end uses metered. Collect building and operating data that affect end use.	Load forecasting by end use. Identify and confirm energy conservation or demand-side management opportunities. Simulation calculations. Rate design.
Specific technology assessment	Measure field performance of building system technology or retrofit measure in individual buildings.	Characterize individual building or technology, occupant behavior, and operation. Account and correct for variations.	Uses detailed audit, submetering, inside temperature, on-site weather, and occupant surveys. May use weekly, hourly, or short-term data.	Technology evaluation. Retrofit performance. Validate models and predictions.
Energy savings measurement and verification	Estimate the impact of a retrofit or other building alteration to serve as the basis for payments or benefits calculation.	Preretrofit consumption is used to create a baseline model. Postretrofit consumption is measured; the difference between the two is savings.	Varies substantially, including verification of potential to provide savings, retrofit isolation, whole-building, or calibrated simulation.	Focused on specific campus, building, component, or system. Amount and frequency of data varies widely between projects.
Building operation and diagnostics	Solve problems. Measure physical or operating parameters that affect energy use or that are needed to model building or system performance.	Typically uses one-time and/or short-term measurement with special methods, such as infrared imaging, flue gas analysis, blower door, or coheating.	Focused on specific building component or system. Amount and frequency of data vary widely between projects.	Energy audit. Identify and solve operation and maintenance, inside air quality, or system problems. Provide input for models. Building commissioning.

at design conditions. The project scope may include reliability, maintenance, design, energy efficiency, sizing, and environmental effects (Phelan et al. 1997a, 1997b).

Savings Measurement and Verification (M&V)

Accountability is increasingly necessary in energy performance retrofits, whether they are performed as part of energy savings performance contracting (ESPC) or performed directly by the owner. In either case, savings measurement and verification (M&V) is an important part of the project. Because the actual energy savings cannot be measured directly, the appropriate role of energy monitoring methodology is to

- Ensure that appropriate data are available, including preretrofit data if retrofits are installed
- Accurately define baseline conditions and assumptions
- Confirm that proper equipment and systems were installed and have the potential to generate the predicted energy savings
- Take postretrofit measurements
- Estimate the energy savings achieved

Proper assessment of an energy retrofit involves comparing before and after energy use, and adjusting for all nonretrofit changes that affected energy use. Weather and occupancy are examples of factors that often change. To assess the effectiveness of the retrofit alone, the influence of these other complicating factors must be removed as best possible. Relationships must be found between energy use and such factors to remove the influence of the factors from the energy savings measurement. These relationships are usually determined through data analysis, not textbook equations. Because data analysis can be conducted in an infinite number of ways, there can be no absolute certainty about the relationship chosen. The need for certainty must be carefully balanced with measurement and analysis costs, recognizing that absolute certainty is not achievable. Among the numerous sources of uncertainty are instrumentation or measurement error, normalization or model error, sampling error, and errors of assumptions. Each source can be minimized to varying degrees by using more sophisticated measurement equipment, analysis methods, sample sizes, and assumptions. However, more certain savings determinations generally follow the law of diminishing returns, where further increases in certainty come at progressively greater expense. Total certainty is seldom achievable, and even less frequently cost-effective (ASHRAE *Guideline* 14).

Other resources are also available. One of the widest known is the *International Performance Measurement and Verification Protocol* (IPMVP 2000). The IPMVP is more general than ASHRAE *Guideline* 14 but provides important background for understanding the larger context of M&V efforts.

Building Diagnostics

Diagnostic projects measure physical and operating parameters that determine the energy use of buildings and systems. Usually, the project goal is to determine the cause of problems, model or improve energy performance of a building or building systems, or isolate effects of components. Diagnostic tests frequently involve one-time measurements or short-term monitoring. To give insight, the frequency of measurement must be several times faster than the rate of change of the effect being monitored. Some diagnostic tests require intermittent, ongoing data collection.

The most basic energy diagnostic for buildings is determining rate of energy use or power for a specific period. The duration may range from essentially a single point in time to a few weeks. The scope of measurement may include the whole building or only one component. The purpose can range from measurement system parameter estimation to verification of nameplate information. Daily or weekly profiles may also be of interest.

A large number of diagnostic measurement procedures are used for energy measurements in residential buildings, particularly single-family. Typical measurements for single-family residences include (1) flue gas and other analysis procedures to determine steady-state furnace combustion efficiency and the efficiency of other end uses, such as air conditioners, refrigerators, and water heaters: (2) fan pressurization tests to measure and locate building envelope air leakage (ASTM *Standard* E779) and tests to measure airtightness of air distribution systems (Modera 1989; Robison and Lambert 1989); and (3) infrared thermography to locate thermal defects in the building envelope and other methods to determine overall building envelope parameters (Subbarao 1988).

Energy systems in multifamily buildings can be much more complex than those in single-family homes, but the types of diagnostics are similar: combustion equipment diagnostics, air leakage measurements, and infrared thermography to identify thermal defects or moisture problems (DeCicco et al. 1995). Some techniques are designed to determine the operating efficiency of steam and hot water boilers and to measure air leakage between apartments.

Diagnostic techniques have been designed to measure the overall airtightness of office building envelopes and the thermal performance of walls (Persily and Grot 1988). Practicing engineers also use a host of monitoring techniques to aid in the diagnostics and analysis of equipment energy performance. Portable data loggers are often used to collect time-synchronized distributed data, allowing multiple data sets (such as chiller performance and ambient conditions) to be collected and quickly analyzed. Similar short-term monitoring procedures are used to provide more detailed and complete commercial building system commissioning. Short-term, in situ tests have also been developed for pumps, fans, and chillers (Phelan et al. 1997a, 1997b).

Diagnostics are also well suited to support development and implementation of building energy management programs (see Chapter 35; Piette et al. 2000). Long-term diagnostic measurements have even supported energy improvements (Liu et al. 1994). Diagnostic measurement projects can generally be designed using procedures adapted to specific project requirements (see the section on Steps for Project Design and Implementation).

Equipment for diagnostic measurement may be installed temporarily or permanently to aid energy management efforts. Designers should consider providing permanent or portable check metering of major electrical loads in new building designs. The same concept can be extended to fuel and thermal energy use.

PROTOCOLS FOR PERFORMANCE MONITORING

Examples of procedures (**protocols**) for evaluating energy savings for projects involving retrofit of existing building energy systems are presented here. These protocols should also be useful to those interested in more general building energy monitoring.

Building monitoring has been significantly simplified and made more professional in recent years by the development of fairly standardized monitoring protocols. Although there may be no way to define a protocol to encompass all types of monitoring applications, repeatable and understandable methods of measuring and verifying retrofit savings are needed. However, following a protocol does not replace adequate project planning and careful assessment of project objectives and constraints.

Residential Retrofit Monitoring

Protocols for residential building retrofit performance can answer specific questions associated with actual measured performance. For example, Ternes (1986) developed a single-family retrofit monitoring protocol, a data specification guideline that identifies important parameters to be measured. Both one-time and time-sequential data parameters are covered, and the parameters are defined carefully to ensure consistency and comparability between experiments. Discrepancies between predicted and actual performance, as measured by the energy bill, are common. This protocol improves on billing data methods in two ways: (1) internal temperature is monitored, which eliminates a major unknown variable in data interpretation; and (2) data are taken more frequently than monthly, which potentially shortens the monitoring duration. Utility bill analysis generally requires a full season of preretrofit and postretrofit data. The single-family retrofit protocol may require only a single season.

Ternes (1986) identified both a minimum set of data, which must be collected in all field studies that use the protocol, and optional extensions to the minimum data set that can be used to study additional issues. See Table 2 for details. Szydlowski and Diamond (1989) have developed a similar method for multifamily buildings.

The single-family retrofit monitoring protocol recommends a before-after experimental design, and the minimum data set allows performance to be measured on a normalized basis with weekly time-series data. (Some researchers recommend daily.) The protocol also allows hourly recording intervals for time-integrated parameters, an extension of the basic data requirements in the minimum data set. The minimum data set may also be extended through optional data parameter sets for users seeking more information.

Table 2 Data Parameters for Residential Retrofit Monitoring

	Recording Period	
	Minimum	**Optional**
Basic Parameters		
House description	once	
Space-conditioning system description	once	
Entrance interview information	once	
Exit interview information	once	
Preretrofit and postretrofit infiltration rates	once	
Metered space-conditioning system performance	once	
Retrofit installation quality verification	once	
Heating and cooling equipment energy consumption	weekly	hourly
Weather station climatic information	weekly	hourly
Indoor temperature	weekly	hourly
House gas or oil consumption	weekly	hourly
House electricity consumption	weekly	hourly
Wood heating use	—	hourly
Domestic hot water energy consumption	weekly	hourly
Optional Parameters		
Occupant behavior		
Additional indoor temperatures	weekly	hourly
Heating thermostat set point	—	hourly
Cooling thermostat set point	—	hourly
Indoor humidity	weekly	—
Microclimate		
Outdoor temperature	weekly	hourly
Solar radiation	weekly	hourly
Outdoor humidity	weekly	hourly
Wind speed	weekly	hourly
Wind direction	weekly	hourly
Shading	once	
Shielding	once	
Distribution system		
Evaluation of ductwork infiltration	once	

Source: Ternes (1986).

Data parameters in this protocol have been grouped into four data sets: basic, occupant behavior, microclimate, and distribution system (Table 2). The minimum data set consists of a weekly option of the basic data parameter set. Time-sequential measurements are monitored continuously during the field study. These are all time-integrated parameters (i.e., appropriate average values of a parameter over the recording period, rather than instantaneous values).

This protocol also addresses instrumentation installation, accuracy, and measurement frequency and expected ranges for all time-sequential parameters (Table 3). The minimum data set (weekly option of the basic data) must always be collected. At the user's discretion, hourly data may be collected, which allows two optional parameters to be monitored. Parameters from the optional data sets may be chosen, or other data not described in the protocol added, to arrive at the final data set.

This protocol standardizes experimental design and data collection specifications, enabling independent researchers to compare project results more readily. Moreover, including both minimum and optional data sets and two recording intervals accommodates projects of varying financial resources.

Commercial Retrofit Monitoring

Several related guidelines have been created for the particular application of retrofit savings (M&V). ASHRAE *Guideline* 14, Measurement of Energy and Demand Savings, provides methods for effectively and reliably measuring the energy and demand savings due to building energy projects. The guideline defines a minimum acceptable level of performance in measuring energy and demand savings from energy conservation measures in residential,

Table 3 Time-Sequential Parameters for Residential Retrofit Monitoring

Data Parameter	Accuracy[a]	Range	Stored Value per Recording Period	Scan Rate[b] Option 1	Scan Rate[b] Option 2
Basic Parameters					
Heating and cooling equipment energy consumption	3%		Total consumption	15 s	15 s
Indoor temperature	0.5 K	10 to 35°C	Average temperature	1 h	1 min
House gas or oil consumption	3%		Total consumption	15 s	15 s
House electricity consumption	3%		Total consumption	15 s	15 s
Wood heating use	0.5 K	10 to 450°C	Average surface temperature or total use time		1 min
Domestic hot water	3%		Total consumption	15 s	15 s
Optional Data Parameter Sets					
Occupant Behavior					
Additional indoor temperatures	0.5 K	10 to 35°C	Average temperature	1 h	1 min
Heating thermostat set point	0.5 K	10 to 35°C	Average set point		1 min
Cooling thermostat set point	0.5 K	10 to 35°C	Average set point		1 min
Indoor humidity	5% rh	10 to 95% rh	Average humidity	1 h	
Microclimate					
Outdoor temperature	0.5 K	−40 to 50°C	Average temperature	1 h	1 min
Solar radiation	30 W/m^2	0 to 1100 W/m^2	Total horizontal radiation	1 min	1 min
Outdoor humidity	5% rh	10 to 95% rh	Average humidity	1 h	1 min
Wind speed	0.2 m/s	0 to 10 m/s	Average speed	1 min	1 min
Wind direction	5°	0 to 360°	Average direction	1 min	1 min

Source: Ternes (1986).
[a]All accuracies are stated values.
[b]Applicable scan rates if nonintegrating instrumentation is used.

commercial or industrial buildings. Such measurements can serve as the basis for commercial transactions between energy services providers and customers who rely on measured energy savings as the basis for financing payments. Three approaches are discussed: whole building, retrofit isolation, and calibrated simulation. The guideline includes an extensive resource on physical measurement, uncertainty, and regression techniques. Example M&V plans are also provided.

The *International Performance Measurement and Verification Protocol* (IPMVP 2000) provides guidance to buyers, sellers, and financiers of energy projects on quantifying energy savings performance of energy retrofits. The Federal Energy Management Program has produced guidelines specific to federal projects, which include many procedures usable for calculating retrofit savings in nonfederal buildings (Schiller Associates 2000).

On a more detailed level, ASHRAE Research Project RP-827 resulted in separate guidelines for the in situ testing of chillers, fans, and pumps to evaluate installed energy efficiency (Phelan et al. 1997a, 1997b). The guidelines specify the physical characteristics to be measured; number, range, and accuracy of data points required; methods of artificial loading; and calculation equations with a rigorous uncertainty analysis.

In addition to these specialized protocols for particular monitoring applications, a number of specific laboratory and field measurement standards exist (see Chapter 56), and many monitoring source books are in circulation.

Finally, a protocol has been developed for field monitoring studies of energy improvements (retrofits) for commercial buildings (MacDonald et al. 1989). Similar to the residential protocol, it addresses data requirements for monitoring studies. Commercial buildings are more complex, with a diverse array of potential efficiency improvements. Consequently, the approach to specifying measurement procedures, describing buildings, and determining the range of analysis must differ.

The strategy used for this protocol is to specify data requirements, analysis, performance data with optional extensions, and a building core data set that describes the field performance of efficiency improvements. This protocol requires a description of the approach used for analyzing building energy performance. The necessary performance data, including identification of a minimum data set, are outlined in Table 4.

Commercial New Construction Monitoring

New building construction offers the potential for monitoring building subsystem energy consumption at a reasonable cost. Information obtained by monitoring operating hours or direct energy consumption can benefit building owners and managers by

- Verifying design intent
- Alerting them to inefficient or improper operation of equipment
- Providing data that can be useful in determining the benefits of alternative operating strategies or replacement equipment
- Evaluating costs of operation for extending occupancy hours for special conditions or event
- Demonstrating the effects of poor maintenance or identifying when maintenance procedures are not being followed
- Diagnosing power quality problems
- Submetering tenants
- Verifying/improving savings of a performance contract

To provide data necessary to improve building systems operation, monitoring should be considered for boilers, chillers, heat pumps, air-handling unit fans, major exhaust fans, major pumps, comfort cooling compressors, lighting panels, electric heaters, receptacle panels, substations, motor control centers, major feeders, service water heaters, process loads, and computer rooms.

Construction documents may include provisions for various meters to monitor equipment and system operation. Some equipment can be specified to have factory-installed hour meters that record actual operating hours of the equipment. Hour meters can also be easily field installed on any electrical motor.

More sophisticated power monitoring systems, with electrical switchgear, substations, switchboards, and motor control centers, can be specified. These systems can monitor energy demand, energy consumption, power factor, neutral current, etc., and can be linked to a personal computer. These same systems can be installed on circuits to existing or retrofit fans, chillers, lighting panels, etc. Some equipment commonly used for improving system efficiency, such as variable-frequency drives, can be provided with capability to monitor kilowatt output, kilowatt-hours consumed, and other variables.

Using direct digital control (DDC) systems for monitoring is particularly appropriate in new construction. These systems can monitor, calculate, and record system status, water use, energy use at the

Table 4 Performance Data Requirements of the Commercial Retrofit Protocol

Projects with Submetering			
	Before Retrofit	**After Retrofit**	
Utility billing data (for each fuel)	12 month minimum	3 month minimum (12 months if weather normalization required)	
Submetered data (for all recording intervals)	All data for each major end use up to 12 months	All data for each major end use up to 12 months	
	Type	**Recording Interval**	**Period Length**
Temperature data (daily maximum and minimum must be provided for any periods without integrated averages)	Maximum and minimum —or— Integrated averages	Daily —or— Same as for submetered data but not longer than daily	Same as billing data length —or— Length of submetering
Projects Without Submetering			
	Before Retrofit	**After Retrofit**	
Utility billing data (for each fuel)	12 month minimum	12 month minimum	
	Type	**Recording Interval**	**Period Length**
Temperature data	Maximum and minimum —or— Integrated averages	Daily	Same as billing data length

main meter or of particular end-use systems, demand, and hours of operation, as well as start and stop building systems, control lighting, and print alarms when systems are not operating within specified limits. Initial specification of the new control system should include specific requirements for sensors, calculations, and trend logging and reporting functions. Special issues related to sensors and monitoring approaches can be found in Piette et al. (2000).

COMMON MONITORING ISSUES

Field monitoring projects require effective management of various professional skills. Project staff must understand the building systems being examined, data management, data acquisition, and sensor technology. In addition to data collection, processing, and analysis, the logistics of field monitoring projects require coordinating equipment procurement, delivery, and installation.

Key issues include the **accuracy** and **reliability** of collected data. Projects have been compromised by inaccurate or missing data, which could have been avoided by periodic sensor calibration and ongoing data verification.

Planning

Many common problems in monitoring projects can be avoided by effective and comprehensive planning.

Project Goals. Project goals and data requirements should be established before hardware is selected. Unfortunately, projects are often driven by the selection of hardware rather than by project objectives, either because monitoring hardware must be ordered several months before data collection begins or because project initiation procedures are lacking. As a result, the hardware may be inappropriate for the particular monitoring task, or critical data points may be overlooked.

Project Costs and Resources. After goal setting, the feasibility of the anticipated project should be reviewed in light of available resources. Projects to which significant resources can be devoted usually involve different approaches from those with more limited resources. This issue should be addressed early on and reviewed throughout the course of the project. Although it is difficult to assess with certainty the cost of an anticipated project at this early stage, rough estimates can be quite helpful.

Data Products. It is important to establish the type and format of the final results calculated from data before selecting data points. Failure to plan these data products first may lead to failure to answer critical questions.

Data Management. Failure to anticipate the typically large amounts of data collected can lead to major difficulties. The computer and personnel resources needed to verify, retrieve, analyze, and archive data can be estimated based on experience with previous projects.

Commitment. Many projects require long-term commitment of personnel and resources. Project success depends on long-term, daily attention to detail and on staff continuity.

Accuracy Requirements. The required accuracy of data products and accuracy of the final data and experimental design needed to meet these requirements should be determined early on. After the required accuracy is specified, the sample size (number of buildings, control buildings, or pieces of equipment) must be chosen, and the required measurement precision (including error propagation into final data products) must be determined. Because tradeoffs must usually be made between cost and accuracy, this process is often iterative. It is further complicated by a large number of independent variables (occupants, operating modes) and the stochastic nature of many variables (weather).

Advice. Expert advice should be sought from others who have experience with the type of monitoring envisioned.

Implementation and Data Management

The following steps can facilitate smooth project implementation and data management:

- Calibrate sensors before installation. Spot-check calibration on site. During long-term monitoring projects, recalibrate sensors periodically. Appropriate procedures and standards should be used in all calibration procedures [see ASHRAE *Guideline* 14 and IPMVP (2000)].
- Track sensor performance regularly. Quick detection of sensor failure or calibration problems is essential. Ideally, this should be an automated or a daily task. The value of data is high because they may be difficult or impossible to reconstruct.
- Generate and review data on a timely, periodic basis. Problems that often occur in developing final data products include missing data from failed sensors, data points not installed due to planning oversights, and anomalous data for which there are no explanatory records. If data products are specified as part of general project planning and produced periodically, production problems can be identified and resolved as they occur. Automating the process of checking data reliability and accuracy can be invaluable in

keeping the project on track and in preventing sensor failure and data loss.

Data Analysis and Reporting

For most projects, the collected data must be analyzed and put into reports. Because the objective of the project is to translate these data into information and ultimately into knowledge and action, the importance of this step cannot be overemphasized. Clear, convenient, and informative formats should be devised in the planning stages and adhered to throughout the project.

Close attention must be paid to resource allocation to ensure that adequate resources are dedicated to verification, management, and analysis of the data and to ongoing maintenance of the monitoring equipment. As a quality control procedure and to make data analysis more manageable, these activities should be ongoing. The data analysis should be carefully defined before the project begins.

STEPS FOR PROJECT DESIGN AND IMPLEMENTATION

This section describes methodology for designing effective field monitoring projects that meet desired goals with available project resources. The task components and relationships among the nine activities constituting this methodology are identified in Figure 1. The activities fall into four categories: project management, project development, resolution and feedback, and production quality and data transfer. Field monitoring projects vary in terms of resources, goals and objectives, data product requirements, and other variables, affecting how methodology should be applied. Nonetheless, the methodology provides a proper framework for advance planning, which helps minimize or prevent implementation problems.

An iterative approach to planning activities is best. The scope, accuracy, and techniques can be adjusted based on cost estimates and resource assessments. The initial design should be performed simply and quickly to estimate cost and evaluate resources. If costs are out of line with resources, adjustments are needed, such as when desired levels of instrumentation exceed the resources available for the project. The planning process should identify and resolve any tradeoffs necessary to execute the project within a given budget. Examples include reducing the scope of the project versus relaxing instrumentation specifications or accuracy requirements. These decisions often depend on what questions the project must answer and which questions can be eliminated, simplified, or narrowed.

One frequent oversight in project planning is failing to reserve sufficient time and resources for later analysis and reporting of data. Unanticipated additional costs associated with data collection and problem resolution should not jeopardize these resources.

Documenting the results of project planning should cover all nine parts of the process. Such a report can become a useful part of an overall project plan that may document other important project information, such as resources to be used, schedule, etc.

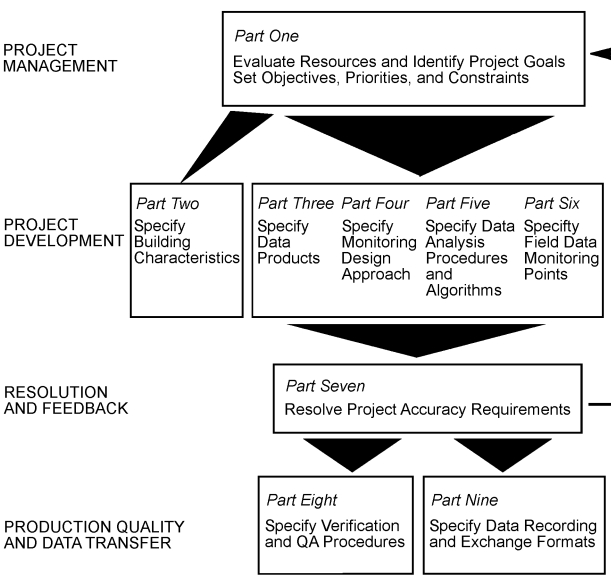

Fig. 1 Methodology for Designing Field Monitoring Projects

Part One: Identify Project Objectives, Resources, and Constraints

Start with a clear understanding of the decision to be made or action to be taken as a result of the project. The goals and objectives statement determines the overall direction and scope of the data collection and analysis effort. The statement should also list questions to be answered by empirical data, noting the error or uncertainty associated with the desired result. Realistic assessment of error is needed because requiring too small an uncertainty leads to an overly complex and expensive project. It is important in monitoring projects that a data acquisition plan be developed and followed with a clear idea of the **research questions** to be answered.

Resource requirements for equipment, personnel, and other items must feed into budget estimates to determine expected funding needed for different project objectives. Scheduling requirements must also be considered, and any project constraints defined and considered. Tradeoffs on budget and objectives require that priorities be established.

Even if a project is not research-oriented, it is attempting to obtain some information, and this can be stated in the form of questions. Research questions can have varying scopes and levels of detail, addressing entire systems or specific components. Some examples of research questions follow:

- Measurement and verification: Have the contractors fulfilled their responsibilities of installing equipment and improving systems to achieve the agreed-upon energy savings?
- Classes of buildings: To an accuracy of 20%, how much energy has been saved by using a building construction/performance standard mandated in the jurisdiction?
- Particular buildings: Has a lapse in building maintenance caused energy performance to degrade?
- Particular components: What is the average reduction in demand charges during summer peak periods because of the installation of an ice storage system in this building?

Research questions vary widely in technical complexity, generally taking one of the following three forms:

- How does the building/component perform?
- Why does the building/component perform as it does?
- Which building/component should be targeted to achieve optimal cost-effectiveness?

The first form of question can sometimes be answered generically for a class of typical buildings without detailed monitoring and analysis, although detailed planning and thorough analysis are still required. The second and third forms usually require detailed monitoring and analysis and, thus, detailed planning.

In general, more detailed and precise goal statements are better. They ensure that the project is constrained in scope and developed to meet specific accuracy and reliability requirements. Usually projects attempt to answer more than one research question, and often consider both primary and secondary questions. All data collected should have a purpose of helping to answer a project question; the more specific the questions, the easier identifying required data becomes.

Part Two: Specify Building and Occupant Characteristics

The measured energy data will not be meaningful later to people who were not involved in the project unless the characteristics of the building being monitored and its use have been documented. To meet this need, a data structure (e.g., a characteristic database) can be developed to describe the buildings.

Building characteristics can be collected at many levels of detail, depending on the type of monitoring project and the parameters that affect results. For projects that determine whole-building performance, it is important to provide at least enough detail to document the following:

- General building type, use, configuration, and envelope (particularly energy-related aspects)
- Building occupant information (number, occupancy schedule, activities)
- Internal loads
- HVAC system descriptive information characterizing key parameters affecting HVAC system performance
- Type and quantity of other energy-using systems
- Any building changes that occur during the monitoring project
- Entrance interview information focusing on energy-related behavior of building occupants before monitoring
- Exit interview information documenting physical or lifestyle changes at the test site that may affect data analysis

The minimum level of detail is known as **summary characteristics** data. **Simulation-level characteristics (**detailed information collected for hourly simulation model input) may be desirable for some buildings. Regardless of the level of detail, the data should provide a context for analysts, who may not be familiar with the project, to understand the building and its energy use.

Part Three: Specify Data Products and Project Output

The objective of a monitoring project is typically not to produce data, but to answer a question. However, the data must be of high quality and must be presented to key decision makers and analysts in a convenient, informative format. The specific **data products** (format and content of data needed to meet project goals and objectives) must be identified and evaluated for feasibility and usefulness in answering project questions identified in Part One. Final data products must be clearly specified, together with the minimum acceptable data requirements for the project. It is important to clearly define an **analysis path** showing what will be calculated and what data will be necessary to achieve desired results. Clear communication is critical to ensure that project requirements are satisfied and factors contributing to monitoring costs are understood.

Evaluation results can be presented in many forms, often as interim and final reports (possibly by heating and/or cooling season), technical notes, or technical papers. These documents must convey specific results of the field monitoring clearly and concisely. They should also contain estimates of the accuracy of the results.

The composition of data presentations and analysis summaries should be determined early to ensure that all critical parameters are identified (Hough et al. 1987). For instance, mock-ups of data tables, charts, and graphs can be used to identify requirements. Previously reported results can be used to provide examples of useful output. Data products should also be prioritized to accommodate possible cost tradeoffs or revisions resulting from other steps in the process such as error analysis (see Part Seven).

Although requirements for the minimum acceptable data results can often be specified during planning, data analysis typically reveals further requirements. Thus, budget plans should include allowances and optional data product specifications to handle additional or unique project output requirements uncovered during data analysis.

Longer-term goals and future information needs should be anticipated and explained to project personnel. For example, a project may have short- and long-term data needs (e.g., demonstrating reductions in peak electrical demand versus demonstrating cost-effectiveness or reliability to a target audience). Initial results on demand reduction may not be the ultimate goal, but rather a step toward later presentations on cost reductions achieved. Thus, it is prudent to consider long-term and potential future data needs so that additional supporting information, such as photographs or testimonials, may be identified and obtained.

Part Four: Specify Monitoring Design Approach

A general monitoring design must be developed that defines three interacting factors: the number of buildings admitted to the study, the monitoring approach (or experimental design), and the level of detail in the data being measured. A less detailed or precise approach can be considered if the number of buildings is increased, and vice versa. If the goal is related to a specific product, the monitoring design must isolate the effects of that product. Haberl et al. (1990) discuss monitoring designs. For example, for retrofit M&V, protocols have been written allowing a range of different monitoring methods, from retrofit verification to retrofit isolation (ASHRAE *Guideline* 14; IPMVP 2000; Schiller Associates 2000). Some monitoring approaches are more suited than others to larger numbers of buildings.

Specifying the monitoring design approach is particularly important because total building performance is a complex function of several variables, changes in which are difficult to monitor and to translate into performance. Unless care is taken with measurement organization and accuracy, uncertainties, errors (noise), and other variations, such as weather, can make it difficult to detect performance changes of less than 20% (Fracastoro and Lyberg 1983).

In some cases, judgment may be required in selecting the number of buildings involved in the project. If an owner seeks information about a particular building, the choice is simple: the number of buildings in the experiment is fixed at one. However, for other monitoring applications, such as drawing conclusions regarding effects in a sample population of buildings, some choice is involved. Generally, error in the derived conclusions decreases as the square root of the number of buildings increases (Box 1978). A specific project may be directed at

- Fewer buildings or systems with more detailed measurements
- Many buildings or systems with less detailed measurements
- Many buildings or systems with more detailed measurements

For projects of the first type, accuracy requirements are usually resolved initially by determining expected variations of measured quantities (dependent variables) about their average values in response to expected variations of independent variables. For buildings, a typical concern is the response of heating and cooling loads to changes in temperature or other weather variables. The response of building lighting energy use to daylighting is another example of the relationship between dependent and independent variables. Fluctuations in response are caused by (1) outside influences not quantified by measured energy use data and (2) limitations and uncertainties associated with measurement equipment and procedures. Thus, accuracy must often be determined using statistical methods to describe mean tendencies of dependent variables.

For projects of the second and third types, the increased number of buildings improves confidence in the mean tendencies of the dependent response(s) of interest. Larger sample sizes are also needed for experimental designs with control groups, which are used to adjust for some outside influences. For more information, see Box (1978), Fracastoro and Lyberg (1983), and Hirst and Reed (1991).

Most monitoring procedures use one or more of the following general experimental approaches:

On-Off. If the retrofit or product can be activated or deactivated at will, energy consumption can be measured in a number of repeated on-off cycles. The on-period consumption is then compared to the off-period consumption (Cohen et al. 1987; Woller 1989).

Before-After. Building, system, or component energy consumption is monitored before and after a new component or retrofit improvement is installed. Changes in factors not related to the retrofit, such as the weather and building operation during the two periods, must be accounted for, often requiring a model-based analysis (Fels 1986; Hirst et al. 1983; Kissock et al. 1992; Robison and Lambert 1989; Sharp and MacDonald 1990). This experimental design is the primary concern of most current building energy monitoring documents (ASHRAE *Guideline* 14; IPMVP 2000; Schiller Associates 2000).

Test-Reference. The building energy consumption data of two "identical" buildings, one with the product or retrofit being investigated, are compared. Because buildings cannot be absolutely identical (e.g., different air leakage distributions, insulation effectiveness, temperature settings, and solar exposure), measurements should be taken before installation as well, to allow calibration. Once the product or retrofit is installed, any deviation from the calibration relationship can be attributed to the product or retrofit (Fracastoro and Lyberg 1983; Levins and Karnitz 1986).

Simulated Occupancy. In some cases, the desire to reduce noise can lead the experimenter to postulate certain standard profiles for temperature set points, internal gains, moisture release, or window manipulation and to introduce this profile into the building by computer-controlled devices. The reference is often given by the test-reference design. In this case, both occupant and weather variations are nearly eliminated in the comparison (Levins and Karnitz 1986).

Nonexperimental Reference. A reference for assessing the performance of a building can be derived nonexperimentally using (1) a normalized, stratified performance database, such as energy use per unit area classified by building type (MacDonald and Wasserman 1989) or (2) a reasonable standard building, simulated by a calculated hourly or bin-method calibrated building energy performance model subject to the same weather, equipment type, and occupancy as the monitored building.

This design, also called **calibrated simulation**, is a secondary concern of current building energy monitoring documents (ASHRAE *Guideline* 14; IPMVP 2000; Schiller Associates 2000).

Engineering Field Test. When an experiment focuses on testing a particular piece of equipment, actual performance in a building is often of interest. The building provides a realistic environment for testing the equipment for reliability, maintenance requirements, and comfort and noise levels, as well as energy usage. Energy consumption of mechanical equipment is significantly affected by the system control strategy. Testing procedures related to determining energy impacts should be designed to incorporate the control strategy of the equipment and its system (Phelan et al. 1997a, 1997b). This type of monitoring and testing can also be used to calibrate computer simulation models of as-built and as-operated buildings, which can then be used to evaluate whole-building energy consumption. The equipment may be extensively instrumented.

Some of the general advantages and disadvantages of these approaches are listed in Table 5 (Fracastoro and Lyberg 1983). Monitoring design choices have been successfully combined (e.g., the before-after and test-reference approaches). Questions to be considered in choosing a monitoring approach include the following:

- Can the building alteration being investigated be turned on and off at will? The on-off design offers considerable advantages.
- Are occupancy and occupant behavior critical? Changes in building tenants, use schedules, internal gains, temperature set points, and natural or forced ventilation practices should be considered because any one of these variables can ruin an experiment if it is not constant or accounted for.
- Are actual baseline energy performance data critical? In before-after designs, time must be allotted to characterize the before case as precisely as the after case. For instances in which heating and cooling systems are being evaluated, data may be required for a wide range of anticipated ambient conditions.
- Is it a test of an individual technology, or are multiple technologies installed as a package being tested? If the effects of individual technologies are sought, detailed component data and careful model-based analyses are required.
- Does the technology have a single mode or multiple modes of operation? Can the modes be controlled to suit the experiment? If many modes are involved, it will be necessary to test over a variety of conditions and conduct model-based analysis (Phelan et al. 1997a, 1997b).

Part Five: Specify Data Analysis Procedures and Algorithms

Data are useless unless they are distilled into meaningful products that allow conclusions to be drawn. Too often, data are collected and never analyzed. This planning step focuses on specifying the minimum acceptable data analysis procedures and algorithms and detailing how collected data will be processed to produce desired data products. In this step, monitoring practitioners should do the following:

- Determine the independent variables and analysis constants to be measured in the field (e.g., fan power, lighting and receptacle power, inside air temperature).
- Develop engineering calculations and equations (algorithms) necessary to convert field data to end products. This may include the use of statistical methods and simulation modeling.
- Specify detailed items, such as the frequency of data collection, the required range of independent variables to be captured in the data set, and the reasons certain data must be obtained at different intervals. For example, 15 min interval demand data is assembled into hourly data streams to match utility billing data.

Determine proper NIST-traceable calibration standards for each sensor type to be used. For details, see the references cited in ASHRAE *Guideline* 14 and IPMVP (2000) for specific types of sensors. However, it is often impractical to implement standards in the field. For example, maintaining the length of straight ductwork required for an airflow sensor is usually difficult in the field, requiring compromise.

Algorithm inputs can be assumed values (such as the energy value of a unit volume of natural gas), one-time measurements (the leakage area of a house), or time-series measurements (fuel consumption and outside and inside temperatures at the site). The algorithms may pertain to (1) utility level aggregates of buildings, (2) particular whole-building performance, or (3) performance of instrumented components.

Chapter 31 of the 2001 *ASHRAE Handbook—Fundamentals* contains a lengthy discussion on modeling procedures, and readers should consult this material for more information on modeling. In this chapter, the discussion is categorized differently, with a view toward procedures and issues related to field energy monitoring projects.

Table 6 provides a guide to selecting an analysis method. The error quotations are rough estimates for a single-building scenario.

Empirical Methods. Although empirical methods are the simplest, they can have large uncertainty and generate little or no information for small sample sizes. The simplest empirical methods are based on annual consumption values, tracking annual numbers and looking for degradation. Questions about building performance relative to other buildings are based on comparing certain performance indices between the building and an appropriate reference.

Table 5 Advantages and Disadvantages of Common Experimental Approaches

Mode	Advantages	Disadvantages
Before-after	No reference building required. Same occupants implies smaller occupant variations. Modeling processes will be mostly identical before/after.	Weather different before/after. More than one heating/cooling season may be needed. Model is required to account for weather and other changes.
Test-reference	One season of data may be adequate. Small climate difference between buildings.	Reference building required. Calibration phase required (may extend testing to two seasons). Occupants in either or both buildings can change behavior.
On-off	No reference building required. One season may be adequate. Modeling processes will be mostly identical before/after. Most occupancy changes will be small.	Requires reversible product. Cycle may be too long if time constants are large. Model is required to account for weather differences in cycles. Dynamic model accounting for transients may be needed.
Simulated occupancy	Noise due to occupancy is eliminated. A variety of standard schedules can be studied.	Not "real" occupants. Expensive apparatus required. Extra cost of keeping building unoccupied.
Nonexperimental reference	Cost of actual reference building eliminated. With simulation, weather variation is eliminated.	Database may be lacking in strata entries. Simulation errors and definition of reference problematic. With database, weather changes usually not possible.
Engineering field test	Information focused on the product of interest. Minimal number of buildings required. Same occupants during the test.	Extensive instrumentation of product processes required. Models required to extrapolate to other buildings and climates. Occupancy effects not determined.

Table 6 Whole-Building Analysis Guidelines

	Class of Method		
Project Goal	**Empirical (Billing Data)***	**Time-Integrated Model***	**Dynamic Model**
Building evaluation	Yes, but expect fluctuations in 20 to 30% range.	Yes, extra care needed beyond 15% uncertainty.	Yes, extra care needed beyond 10% uncertainty.
Building retrofit evaluation	Not generally applicable using monthly data, unless large samples are used. Requires daily data and various normalization techniques for reasonable accuracy.	Yes, but difficult beyond 15% uncertainty. Method cannot distinguish multiple retrofit effects.	Yes, can resolve 5% change with short-term tests. Can estimate multiple retrofit effects.
Component evaluation	Not applicable.	Not applicable unless submetering is done to supplement.	Yes, about 5% accuracy, but best with submetering.

Note: Error figures are approximate for total energy use in a single building. All methods improve with selection of more buildings.

*Accuracy can be improved by decreasing time step to weekly or daily. These methods are of little use when the *outdoor* temperature approaches the *balance* temperature.

ASHRAE *Standard* 105 gives an example of how a database could be established for this purpose.

For commercial buildings, the most common index is the **energy use intensity** (EUI), which is annual consumption, either by fuel type or summed over all fuel types, divided by the gross floor area. Comparison is often made only on the basis of general building type, which can ignore potentially large variations in how much floor area is heated or cooled, climate, the number of workers in a building, the number and type of computers in a building, and HVAC systems. Such variations can be accommodated somewhat by stratifying the database from which the reference EUI is chosen. Computer simulations are often used to set reasonable comparison values.

The Commercial Buildings Energy Consumption Survey database, summarized in EIA (1998) and in Chapter 35, has been used to develop energy use benchmarking methods for office buildings and schools in the United States (for more information, visit www.energystar.gov and follow links for building types of interest). Benchmarking methods for additional building types are also planned.

Initial work in this area covered only electricity use (Sharp 1996), but the methods have been extended to cover all fuels for office buildings. Results show that electricity use of office buildings is most significantly explained by the number of workers in the building, the number of personal computers, whether the building is owner-occupied, and the number of operating hours each week. Only a subset of these parameters might be used to determine a benchmark within a specific census division.

Simple empirical methods applied to retrofit applications should include at least some periods of data on daily energy use and average daily temperature (recorded locally) to account for variations in occupancy and building schedules. Monthly EUI or billing data provide more information for empirical analysis and can be used for extended analysis of energy impacts of retrofit applications, for example, in **conditional demand analysis** (Hirst and Reed 1991). Monthly data can also be used to detect billing errors, improper equipment operation during unoccupied hours, and seasonal space condition problems (Haberl and Komor 1990a, 1990b). Daily data are often used in these analyses, and raw hourly total building consumption data, when available, provide more detailed information on occupied versus unoccupied performance. Hourly, daily, monthly, and annual EUI across buildings can be directly compared when reduced to average power per unit area (power density). To avoid false correlations, the method of analysis should have statistical significance that can be traced to realistic parameters (Haberl et al. 1996).

Model-Based Methods. These techniques allow a wide range of additional data normalization to potentially improve the accuracy of comparisons and provide estimates of cause-effect relations. The analyst must carefully define the system and postulate a useful form of the governing energy balance/system performance equation or system of equations. Explicit terms are retained for equipment or processes of particular interest. As part of the data analysis, whole-building data (driving forces and thermal or energy response) are used to determine the model's significant parameters.

The parameters themselves can provide insight, although parameter interpretation can be difficult, particularly with time-integrated billing data methods. The model can then be used for a number of normalization processes as well as future diagnostic and control applications. Two general classes of models are used in analysis methods: time-integrated methods and dynamic techniques (Balcomb et al. 1993).

Time-integrated methods. Based on algebraic calculation of the building energy balance, time-integrated methods are often used before data comparison to correct annual consumption for variations in outside temperature, internal gains, and internal temperature (Busch et al. 1984; Claridge et al. 1991; Fels 1986; Haberl and Claridge 1987). This type of correction is essential for most retrofit applications.

Time-integrated methods can be used with whole-building energy consumption data (billing data) or with submetered end-use data. For example, standard time-integrated methods are often used to separately integrate end-use consumption data on heating, cooling (Ternes and Wilkes 1993), domestic water heating, and others for comparison and analysis. Time-integrated methods are generally reliable, as long as the following three conditions are accounted for:

- *Appropriate time step*. Generally, the time step should be as long as or longer than the response time of the building or building system for which energy use is being integrated. For example, the response of daylighting controls to natural illumination levels can be rapid, allowing short time steps for data integration. In contrast, the response of cooling system energy use to changes in cooling load can be comparatively slow. In this instance, either a time step long enough to average over these slow variations or a dynamic model should be used. In general, an appropriate time step should account for the physical behavior of the energy system(s) and the expression of this behavior in model parameters.
- *Linearity of model results*. Generally, time-integrated models should not be applied to data used to estimate nonlinear effects. Air infiltration, for example, is nonlinear when estimated using wind speed and inside/outside temperature difference data in certain models. Estimation errors would result if these parameters were independently time-integrated and then used to calculate air infiltration. Such nonlinear effects should be modeled at each time step (each hour, for example).
- *End-use uniformity within data set*. End-use data sets should be **uniform** (i.e., should not inadvertently contain observations with measurements of end uses other than those intended). During mild weather, for example, HVAC systems may provide both heating and cooling over the course of a day, creating data observations of both heating and cooling measurements. In a time-integrated model of heating energy use, these cooling energy observations would lead to error. Such observations should be identified or otherwise flagged by their true end use.

For whole-building energy consumption data (billing data), reasonable results can be expected from heating analysis models when the building is dominantly responsive to inside-outside temperature differences. Billing data analysis yields little of interest when internal gains are large compared to skin loads, as in large commercial buildings and industrial applications. Daily, weekly, and monthly whole-building heating season consumption integration steps have been employed (Claridge et al. 1991; Fels 1986; Sharp and MacDonald 1990; Ternes 1986). Cooling analysis results have been less reliable because cooling load is not strictly proportional to variable-base cooling degree-days (Fels 1986; Haberl et al. 1996; Kissock et al. 1992). Problems also arise when solar gains are dominant and vary by season.

Dynamic Techniques. Dynamic models, both **macrodynamic** (whole-building) or **microdynamic** (component-specific), offer great promise for reducing monitoring duration and increasing conclusion accuracy. Furthermore, individual effects from multiple measures and system interactions can be examined explicitly. Dynamic whole-building analysis is generally accompanied by detailed instrumentation of specific technologies.

Dynamic techniques create a dynamic physical model for the building, adjusting model parameters to fit experimental data (Duffy et al. 1988; Subbarao 1988). In residential applications, computer-controlled electric heaters can be used to maintain a steady interior temperature overnight, extracting from these data an experimental value for the building steady-state load coefficient. A cooldown period can also be used to extract information on internal building mass thermal storage. Daytime data can be used to renormalize the building response (computed from a microdynamic model) to solar radiation, which is particularly appropriate for buildings with glazing areas over 10% of the building floor area (Subbarao et al. 1986). Once the data with electric heaters have been taken, the building can be used as a dynamic calorimeter to assess the performance of auxiliary heating and cooling systems.

Similar techniques have been applied to commercial buildings (Burch et al. 1990; Norford et al. 1985). In these cases, delivered energy from the HVAC system must be monitored directly in lieu of using electric heaters. Because ventilation is a major variable term in the building energy balance, the outside airflow rate should also be monitored directly. Simultaneous heating and cooling, common in large buildings, requires a multizone treatment, which has not been adequately tested in any of the dynamic techniques.

Equipment-specific monitoring guidelines using dynamic modeling have been successfully tested in a variety of applications. For fans and pumps, relatively simple regression techniques from short-term monitoring provided accurate estimates of annual energy consumption when combined with an annual equipment load profile. For chillers, a thermodynamic model used with short-term monitoring captured the most important operating parameters for estimating installed annual energy performance. In all cases, the key to accurate model results was capturing a wide enough range of the independent load variable in monitored data to reflect annual operating characteristics (Phelan et al. 1997a, 1997b).

Part Six: Specify Field Data Monitoring Points

Careful specification of field monitoring points is critical to identifying variables that need to be monitored or measured in the field to produce required data.

The analysis method determines the data to be measured in the field. The simplest methods require no onsite instrumentation. As methods become more complex, data channels increase. For engineering field tests conducted with dynamic techniques, up to 100 data channels may be required.

Because metering projects are often conducted in buildings with changing conditions, special consideration must be given to identifying and monitoring significant changes in climate, systems, and operation during the monitoring period. Additional monitoring points may be required to measure variables that are assumed to be constant, insignificant, or related to other measured variables to draw sound conclusions from the measurements. Because the necessary data may be obtained in several ways, data analysts, equipment installers, and data acquisition system engineers should work together to develop tactics that best suit the project requirements. It is important to anticipate the need for supplemental measurements in response to project needs that may not become apparent until actual equipment installation occurs.

The cost of data collection is a nonlinear function of the number, accuracy, and duration of measurements that must be considered while planning within budget constraints. Costs per data point typically decrease as the number of points increases, but increase as accuracy requirements increase. Duration of monitoring can have many different effects. If the extent of data applications is unknown, such as in research projects, consideration should be given to the value of other concurrent measurements because the incremental cost of alternative analyses may be small.

For any project involving large amounts of data, data quality verification (see Part Eight) should be automated (Lopez and Haberl 1992). Although this may require adding monitoring points to facilitate energy balances or redundancy checks, the added costs are likely to be offset by savings in data verification for large projects.

If multiple sites are to be monitored, common protocols for selecting and describing all field monitoring points should be established so data can be more readily verified, normalized, compared, and averaged. Protocols also add consistency in selecting monitoring points. Pilot installations should be conducted to provide data for a test of the system and to ensure that the necessary data points have been properly specified and described.

Monitoring Equipment. General considerations in selecting monitoring equipment include the following:

- Evaluate equipment thoroughly under actual test conditions before committing to large-scale procurement. Particular attention should be paid to any sensitivity to power outages and to protection against power surges and lightning.
- Consider local setup and testing of complex data acquisition systems that are to be installed in the field.
- Avoid unproven data acquisition equipment (Sparks et al. 1992). Untested equipment, even if donated, may not be a good value.
- Consider costs and benefits of remote data interrogation and programming.
- Evaluate quality and reliability of data loggers and instrumentation; these issues may be more important than cost, particularly when data acquisition sites are distant.
- Verify vendor claims by calling references or obtaining performance guarantees.
- Consider portable battery-powered data loggers in lieu of hardwired loggers if the monitoring budget is limited and the length of the monitoring period is less than a few months.
- Ensure that monitoring equipment and installation methods are consistent with prevailing laws, building codes, and standards of good practice.

Using a building energy management system or direct digital control systems for data acquisition may decrease costs. This should be considered only when the sensors and their accuracy and limitations (scan rate, etc.) are thoroughly understood. When merging data from two data acquisition systems, problems may arise such as differing reliability and low data resolution (e.g., 1 kW resolution of a circuit which draws 10 kW fully loaded). These problems can often be avoided, however, by adding appropriate sensors and setting up custom logging or calculations with point, memory, and programming capacity.

Once the required field data monitoring points are specified, these requirements should be clearly communicated to all members of the project team to ensure that the actual monitoring points are accurately described. This can be accomplished by publishing handbooks for measurement plan development and equipment installation and by outlining procedures for diagnostic tests and technology assessments.

Because hardware needs vary considerably by project, specific selection guidelines are not provided here. However, general characteristics of data acquisition hardware components are shown in Table 7. Some typical concerns for selecting data acquisition hardware are outlined in Table 8. In general, data logger and instrumentation hardware should be standardized, with replacements available in the event of failure. Also consider redundant measurements for critical data components that are likely to fail, such as modems, flowmeters, shunt resistors on current transformers, and devices with moving parts (O'Neal et al. 1993). Certain measurements that are more difficult to obtain accurately than others because of instrumentation limitations are summarized in Table 9.

Safety must be considered in equipment selection and installation. Installation teams of two or more individuals will reduce risks. When contemplating thermal metering, the presence of asbestos insulation on water piping should be determined. Properly licensed trades personnel, such as an electrician or welder, should be a fundamental part of any team installing electrical monitoring equipment.

To prevent inadvertent tampering, occupants and maintenance personnel should be carefully briefed on what is being done and the purpose of sensors and equipment. Data loggers should have a dedicated (non-occupant-switchable) hard-wired power supply to prevent accidental power loss.

Sensors. Sensors should be selected to obtain each measurement on the field data list. Next, conversion and proportion constants should be specified for each sensor type, and the accuracy, resolution, and repeatability of each sensor should be noted. Sensors should be calibrated before they are installed in the field, preferably with a NIST-traceable calibration procedure. They should be checked periodically for drift, recalibrated, and then postcalibrated at the conclusion of the experiment (Haberl et al. 1996). Instrument calibration is particularly important for flow and power measurement.

Particular attention must be paid to sensor location. For example, if the method requires an average inside temperature, examine the potential for internal temperature variation; data from several temperature sensors must often be averaged. Alternatively, temperature sensors adjacent to HVAC thermostats detect the temperature to which the HVAC equipment reacts.

Scanning and Recording Intervals. Measurement frequency and data storage can affect the accuracy of results. Scanning differs from storage in that data channels may be read (scanned) many times per second, for example, whereas average data may be recorded and stored every 15 min. Most data loggers maintain temporary storage registers, accumulating an integrated average of channel readings from each scan. The average is then recorded at the specified interval.

After the channel list is compiled and sensor accuracy requirements established, scan rates should be assigned. Some sensors, such as inside and outside temperature sensors, may require low scan rates (once every 5 min). Others, such as total electric sensors, may contain high-frequency transients that require rapid sampling (many times per second). The scan rate must be fast enough to ensure that all significant effects are monitored.

The maximum sampling rate is usually programmed into the logger, and averages are stored at a specified time step (hourly). Some loggers can scan different channels at different rates. The logger's interrupt capability can also be used for rapid, infrequent transients. Interrupt channels signal the data logger to start monitoring an event only once it begins. In some cases, online computation of derived quantities must be considered. For example, if heat flow in an air duct is required, it can be computed from a differential temperature measurement multiplied by an air mass flow rate determined from a one-time measurement. However, it should be computed and totaled only when the fan is operating.

Part Seven: Resolve Data Product Accuracies

Data collected by monitoring equipment are usually used for the following purposes:

- Direct reporting of primary measurement data
- Reporting of secondary or deduced quantities (e.g., thermal energy consumed by a building, found by multiplying mass flow rate and temperature difference
- Subsequent interpretation and analyses (e.g., to develop a statistical model of energy used by a building versus outside dry-bulb temperature)

In all three cases, the value of the measurements is dramatically increased if the associated uncertainty can be quantified.

Table 7 General Characteristics of Data Acquisition Systems

Types of Data Acquisition Systems (DAS)	Typical Use	Typical Data Retrieval	Comments
Manual readings	Total energy use	Monthly or daily written logs	Human factors may affect accuracy and reading period. Data must be manually entered for computer analysis.
Pulse counter, cassette tapes (1 to 4 channels)	Total energy use (some end use)	Monthly pickup of cassette tapes	Data loss from cassette is a common problem. Pulse data must be read and converted before it can be analyzed.
Pulse counter, solid state (1, 4, or 8 channels)	Total energy use (some end use)	Polled by telephone to mainframe or minicomputer	Computer hardware and software is needed for transfer and conversion of pulse data. Can be expensive. Can handle large numbers of sites. User-friendly.
Stick-on battery powered logger (1 to 8 channels)	Diagnostics, technology assessment, end use	Monthly manual download to PC	Very useful for remote sites. Can record pulse counts, temperature, etc., up to 1500 records.
Plug-in A/D boards for PCs	Diagnostics, technology assessment, control	On-site real-time collection and storage	Usually small-quantity, unique applications. PC programming capability needed to set up data software and configure boards.
Simple field DAS (usually 16 to 32 channels)	Technology assessment, residential end use (some diagnostics)	Phone retrieval to host computer for primary storage (usually daily to weekly)	Can use PCs as hosts for data retrieval. Good A/D conversion available. Low cost per channel. Requires programming skills to set up field unit and configure communications for data transfer.
Advanced field DAS (usually >40 channels/ units)	Diagnostics, energy control systems, commercial end use	On-site real-time collection and data storage, or phone retrieval	Usually designed for single buildings. Can be PC-based or stand-alone unit. Can run applications/diagnostic programs. User-friendly.
Direct digital control or building automation system	On-site diagnostics, energy measurement and verification	Proprietary data collection procedures, manual or automated export to spreadsheet.	Requires significant coordination with building operation personnel. Sensor accuracy, calibration, and installation require confirmation. Good for projects with limited instrumentation budget.

Table 8 Practical Concerns for Selecting and Using Data Acquisition Hardware

Components	Field Application Concerns
Data logger unit and peripherals	• Select equipment for field application. • Equipment should store data in electronic form such as on floppy disks, on magnetic tape, or in memory for easy transfer to the computer that will perform the analysis. • Remote programming capability should be available to minimize onsite software modifications. • Avoid equipment with cooling fans. • Use high-quality, reliable modems. • Make sure logger and modem reset after power outage.
Cabling and interconnection hardware	• Use only signal-grade cable—shielded, twisted-pair with drain wire for analog signals. • Mitigate sources of common mode and normal mode signal noise.
Sensors	• Use rugged, reliable sensors that are rated for field application. • Use a signal splitter if sharing existing sensors or signals with other recorders or energy management control system (EMCS). • Select ranges so sensors operate at 50 to 75% of full scale. • Choose sensors that do not require special signal conditioning. • Precalibrate sensors and recalibrate periodically. • When possible, use redundant channels to cross-check critical channels that can drift.

Basic Concepts. Uncertainty can be better understood in terms of confidence limits. Confidence limits define the range of values that can be expected to include the true value with a stated probability (ASHRAE *Guideline* 2). Thus, a statement that the 95% confidence limits are 5.1 to 8.2 implies that the true value is between 5.1 and 8.2 in 19 out of 20 predictions or, more loosely, that we are 95% confident that the true value lies between 5.1 and 8.2. For a given set of n observations with normal (Gaussian) error distribution, the total variance about the mean predicted value $\bar{X}'$ provides a direct indication of the confidence limits. Thus the "true" mean value X' of the random variable is bounded as follows:

Table 9 Instrumentation Accuracy and Reliability

Instrument	Problems
Hygrometers	Drift, saturation and accuracy over time, need for calibration to remove temperature dependence; aspirated systems need to be cleaned periodically. Chilled mirror systems require frequent maintenance.
Flowmeters	Need for calibration, reliability. Moving parts prone to failure. Pipe size must be verified prior to calibration or installation.
Heatflow meters	60 Hz noise from surroundings, calibration.
Single-ended voltage	Grounding problems, spurious line voltages, 60 Hz noise.
Outdoor air temperature sensor	Must be properly shielded from solar radiation. Aspiration may reduce solar radiation effects but decrease long-term reliability.
RTD sensors	Signal wire length affects readings.
Power meters	Polarity of current transformers (CTs) often marked incorrectly, problems with shunt resistors and CT output. Devices should be checked before installation.

$$\bar{X}' \pm t_{\alpha/2,n-1}\sqrt{\sigma^2/n} \tag{1}$$

where

α = level of significance

$\overline{X}'$ = mean predicted value of random variable X
$t_{\alpha/2,n-1}$ = t-statistic with probability of $1 - \alpha/2$ and $n - 1$ degrees of freedom (tabulated in most statistical textbooks)
n = number of observations, with Gaussian error distribution
σ^2 = estimated measurement variance

The terms **accuracy** and **precision** are often used to distinguish between bias errors and random errors. A set of measurements with small bias errors is said to have high accuracy, and a set of measurements with small random errors is said to have high precision. In repeated measurements of a given sample by the same technique (single-sample data), each measurement has the same bias. Bias errors include those that are (1) known and can be calibrated out, (2) negligible and are ignored, and (3) estimated and are included in the uncertainty analysis. It is usually difficult to estimate bias limits, and this effect is often overlooked by most practitioners. However, a proper error analysis should include bias error, which is usually written as a plus-minus error. ASME *Standard* PTC 19.1 has a more complete discussion.

Because bias errors b_m and random errors ε_m are usually uncorrelated, measurement variance σ^2 can be expressed as

$$\sigma^2_{meas}(b_m, \varepsilon_m) = \sigma^2(b_m) + \sigma^2(\varepsilon_m) \tag{2}$$

For further information on uncertainty, see Chapter 14 of the 2001 *ASHRAE Handbook—Fundamentals.* For more information on uncertainty calculation methods related specifically to building energy savings monitoring, see *ASHRAE Guideline* 14, Annex B.

Primary Measurement Uncertainty. Sensor and measuring equipment manufacturers usually specify measurement variances; frequent recalibration minimizes bias errors. As indicated by Equation (1), increasing the number of measurements n reduces the uncertainty bounds.

Uncertainty in Derived Quantities. Once a specific algorithm or equation for obtaining final data from physical measurements has been established, standard techniques can be used to incorporate primary measurement uncertainties into the final data product. For the random errors, the well-known Kline and McClintock (1953) error propagation method, based on a first-order Taylor series expansion, is widely used to determine measurement uncertainties in derived variables in single-sample experiments. Bias errors are difficult to account for; the usual practice is to calibrate them out and exclude them from the uncertainty analysis.

Uncertainty in Statistical Regression Models. Statistical regression models developed from measured data are usually used for predictive purposes. Measurement errors are much smaller than model errors, which arise because the regression model is imperfect; that is, it is unable to explain the entire variation in the regressor variable (Box 1978). Measurement error is inherently contained in the identified model, so total prediction variance is simply given by the model prediction uncertainty.

Determining prediction errors from regression models is subject to different types of problems. The various sources of error can be classified into three categories (Reddy et al. 1998):

- Model *misspecification* errors occur because the functional form of the regression model is usually an approximation of the true driving function of the response variable
- Model *prediction* errors occur because a model is never perfect
- Model *extrapolation* errors occur when a model is used for prediction outside the region covered by the data from which the model was developed. Models developed from short data sets, which do not satisfactorily represent the annual behavior of the system, are subject to this error. This error cannot be quantified in statistical terms alone, but certain experimental conditions are likely to lead to accurate predictive models. This falls under the purview of experimental design (Box 1978).

Misspecification and extrapolation errors are likely to introduce bias and random error. If ordinary least-squares regression is used for parameter estimation, and if the model is subsequently used for prediction, model prediction will be purely random. Thus, models identified from short data sets and used to predict seasonal or annual energy use are affected by misspecification and extrapolation errors.

The least-squares method of calculating linear regression coefficients cannot produce unbiased estimators of slope and intercept if there are errors associated with measuring the predictor variable. The uncertainty analysis methodology developed for in situ equipment testing uses standard linear regression practices to find the functional relationship and then estimates the increased uncertainty in the regression prediction because of random and bias errors in both variable measurements (Phelan et al. 1996).

Experimental Design. Errors can also be estimated based on historical experience (e.g., using results from previous similar projects). Alternatively, a pilot study can obtain an estimate of potential errors in a proposed analysis. Some estimate of potential error must be available to determine whether project goals and objectives are reasonable.

Estimating data uncertainty is one part of the iterative procedure associated with proper experimental design. If the final data product uncertainty determined using the given evaluation procedure is unacceptable, uncertainty can be reduced in one or more of the following ways:

- Reducing overall measurement uncertainty (improving sensor precision)
- Increasing the duration of the monitoring period to average out stochastic variations
- Increasing the number of buildings tested

On the other hand, if simulations indicate that the expected bias in the final data products is unacceptable, the bias may be reduced by one or more of the following steps:

- Adding sensors to get an unbiased measurement of the quantity
- Using more detailed models and analysis procedures
- Increasing data acquisition frequency, combined with a more detailed model, to address biases from sensor or system nonlinearities.

Accuracy Versus Cost. The need for accuracy must be carefully balanced against measurement and analysis costs. Accuracy loss can stem from instrumentation or measurement error, normalization or model error, sampling or statistical error, and errors of assumptions. Each of these sources can be controlled to varying degrees. However, in general, more accurate methods follow the law of diminishing returns, in which further reductions in error come at progressively greater expense.

Because of this tradeoff, the optimal measurement solution is usually found by an iterative approach, where incremental improvements in accuracy are assessed relative to the increase in measurement cost. Such optimization requires that a value be placed on increasing levels of accuracy. One method of evaluating the uncertainty of a proposed method is to calculate results using the highest and lowest values in the confidence interval. The difference between these values can be translated into a monetary amount that is at risk. The question that must be answered is whether further measurement investment is warranted to reduce this risk.

Part Eight: Specify Verification and Quality Assurance Procedures

Establishing and using data quality assurance (QA) procedures can be very important to the success of a field monitoring project. The amount and importance of the data to be collected help determine the extent and formality of the QA procedures. For most projects, the entire data path, from sensor installation to procedures that generate results for the final report, should be considered for verification tests. In addition, the data flow path should be checked

Table 10 Quality Assurance Elements

Time Frame	Hardware	Engineering Data	Characteristics Data
Initial start-up	Bench calibration (1) Field calibration (1) Installation verification (1)	Installation verification (1) Collection verification (1,2) Processing verification (1,2) Result production (1,2)	Field verification (1) Completeness check (1) Reasonableness check (1,2) Result production (1,2)
Ongoing	Functional testing (1) Failure mode diagnosis (3) Repair/maintenance (4) Change control (1)	Quality checking (2) Reasonableness checking (2) Failure mode diagnosis (3) Data reconstruction (4) Change control (1)	Problem diagnosis (3) Data reconstruction (4) Change control (1)
Periodic	Preventive maintenance (1) Calibration (1)	Summary report preparation and review (2)	Scheduled updates/resurveys (1) Summary report preparation and review (2)

(1) Actions to ensure good data. (2) Actions to check data quality. (3) Actions to diagnose problems. (4) Actions to repair problems.

routinely for failure of sensors or test equipment, as well as unexpected or unauthorized modifications to equipment.

QA often requires complex data handling. Building energy monitoring projects collect data from sensors and manipulate those data into results. Data handling in a project with only a few sensors and required readings can consist of a relatively simple data flow on paper. Computers, which are generally used in one or more stages of the process, require a different level of process documentation because much of what occurs has no direct paper trail.

Computers facilitate collection of large data sets and increase project complexity. To maximize automation, computers require development of specific software. Often, separate computers are involved in each step, so passing information from one computer to another must be automated in large projects. To move data as smoothly as possible, an automated **data pipeline** should be developed; this minimizes the delay from data collection to results production and maximizes the cost-effectiveness of the entire project.

Because collected data are valuable, data back-up procedures must also be part of QA. At a minimum, the basic data, either raw or first-level processed, should be stored in at least one and preferably two different back-up locations, apart from the main data storage location, to allow data recovery in case of hardware failure, fire, vandalism, etc. Back-ups should occur at regular intervals, probably not less than weekly for larger projects.

Automated data verification should be used when possible. Frequent data acquisition (preferably automated) with a quality control review of summarized and plotted data is essential to ensure that reliable data are collected. Verification procedures should be performed at frequent intervals (daily or weekly), depending on the importance of missing data. This minimizes data loss because of equipment failure and/or changes at a building site. It also allows processed information to be applied quickly.

The following QA actions should take place:

- Calibrate hardware and establish a good control procedure for collection of data. Use NIST-traceable calibration methods.
- Verify data, check for reasonableness, and prepare a summary report to ensure the quality of the data after collection.
- Perform initial analysis of the data. Significant findings may lead to changes in procedures for checking data quality.
- Thoroughly document and control procedures applied to remedy problems. These procedures may entail changes in hardware or collected data (such as data reconstruction), which can have a fundamental effect on the results reported.
- Archive raw data obtained from the site to ensure project integrity.

Three aspects of a monitoring project that require QA are shown in Table 10: hardware, engineering data, and characteristics data. Three QA reviews are necessary for each aspect: (1) initial QA confirms that the project starts correctly; (2) ongoing QA confirms that information collected by the project continues to satisfy quality requirements; and (3) periodic QA involves additional checks, established at the beginning of the project, to ensure continued performance at an acceptable quality level.

Information about data quality and the QA process should be readily available to data users. Otherwise, significant analytical resources may be expended to determine data quality, or the analyses may never be performed because of uncertainties.

Part Nine: Specify Recording and Data Exchange Formats

This step specifies the formats in which data will be supplied to the end user or other data analysts. Both raw and processed (adjusted for missing data or anomalous readings) data formats should be specified. In addition, if supplemental analyses are planned, the medium and format to be used (type of disk, possibly magnetic tape type, spreadsheet, character encoding standard) should be specified. These requirements can be determined by analyzing the software data format specifications. Common formats for raw data are comma- and blank-delimited American Standard Code for Information Exchange (ASCII), which do not require data conversion.

Data documentation is essential for all monitoring projects, especially when several organizations are involved. Data usability is improved by specifying and adhering to data recording and exchange formats. Most data transfer problems are related to inadequate documentation. Other problems include hardware or software incompatibility, errors in electronic storage media, errors or inconsistencies in the data, and transmittal of the wrong data set. The following precautions can prevent some of these problems:

- Provide documentation to accompany the data transfer (Table 11). Because these guidelines apply to general data, models, programs, and other types of information, the items listed in Table 11 may not apply to every case.
- Provide documentation of transfer media, including the computer operating system, software used to create the files, media format (ASCII, binary), and media characteristics (specific manufacturer if necessary, storage capacity, tracks, density, record length, block, size).
- Provide procedures to check the accuracy and completeness of data transfer, including statistics or frequency counts for variables and hard-copy versions of the file. Test input data and corresponding output results for models on other programs.
- Keep all raw data, including erroneous records.
- Convert and correct data; save routines for later use.
- Limit equipment access to authorized individuals.
- Check incoming data soon after they are collected, using simple time-series and x-y inspection plots.
- Automate as many routines as possible to avoid operator error.

Table 11 Documentation Included with Computer Data to be Transferred

1. Title and/or acronym
2. Contact person (name, address, phone number)
3. Description of file (number of records, geographic coverage, spatial resolution, time period covered, temporal resolution, sampling methods, uncertainty/reliability)
4. Definition of data values (variable names, units, codes, missing value representation, location, method of measurement, variable derivation)
5. Original uses of file
6. Size of file (number of records, bytes)
7. Original source (person, agency, citation)
8. Pertinent references (complete citation) on materials providing additional information
9. Appropriate reference citation for the file
10. Credit line (for use in acknowledgments)
11. Restrictions on use of data/program
12. Disclaimer (examples follow):
    - Unverified data; use at your own risk.
    - Draft data; use with caution.
    - Clean data to the best of our knowledge. Please let us know of any possible errors or questionable values.
    - Program under development.
    - Program tested under the following conditions (conditions specified by author).

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