

CHAPTER 42. BUILDING ENERGY AND WATER MONITORING

BUILDING energy monitoring was conducted on a large scale in the 1980s and 1990s. Project requirements were often not addressed adequately in these projects, and this chapter was developed to address these and capture new insights. The intent of monitoring projects is to provide realistic, empirical information from field data to enhance understanding of actual building energy performance and help quantify changes in performance over time. Although different building energy monitoring projects can have different objectives and scopes, all have several commonalities 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 includes 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. The scope of this chapter has been expanded to include water, water monitoring, and associated water efficiency project measurement and verification. A section on small projects is also included, to show how the methodology can be simplified.

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 [BAS]). 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 or water use. It is important to determine the accuracy needed to meet objectives, the type of monitoring needed to provide the desired accuracy, and whether such accuracy justifies the cost of an instrumented approach.

Instrumented field monitoring projects generally involve a data acquisition system (DAS), which is typically comprised of sensors and data-recording devices (e.g., data loggers) or a suitably equipped BAS. 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. Useful building water performance data cover whole buildings and end use component breakdowns, potable fixtures, HVAC equipment (makeup water), water heating (boiler feed water), 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 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 in a single facility. Monitoring projects range from broad research studies to very specific, contractually required savings verifications carried out by performance contractors. Auditing examines energy performance using observations and measured data, which are detailed in ASHRAE (2011). BSR/ASHRAE/ACCA *Standard* 211-2018 specifies minimum requirements for such audits.

All practitioners should use accepted standards and protocols of monitoring practices to communicate results. Key elements in this monitoring 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 or water savings from energy service performance contracts can be specified on either a whole-building or component basis. Monitoring requirements for each approach vary widely and must be carefully matched to the specific project. Procedures in ASHRAE *Guideline* 14-2014 can be used to determine monitoring requirements. Performance measurement protocols for commercial buildings (new or retrofit construction), including energy, water, and indoor environmental quality, are presented in ASHRAE (2010). Best practices for performance measurement are given in ASHRAE (2012).

1. REASONS FOR ENERGY OR WATER 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 validation and analysis procedures, duration and frequency of data collection, and instrumentation, are common to most, if not all, projects.

Table 1 Characteristics of Major Monitoring Project Types

Project Type	Goals and Objectives	General Approach	Level of Detail	Uses
Energy or water end use assessment	Determine characteristics of specific energy or water end uses in building.	Often uses large, statistically designed sample. Monitor energy or water 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. Energy or water audit to identify and confirm energy or water 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, sub-metering, indoor temperature, on-site weather, and occupant surveys. May use weekly, hourly, or short-term data.	Technology evaluation. Retrofit performance. Validate models and predictions.
Energy or water savings measurement and verification	Estimate the impact of retrofit, commissioning, or other building alteration to serve as basis for payments or benefits calculation.	Pre-retrofit consumption is used to create baseline model. Post-retrofit consumption is measured; the difference between the two is savings.	Varies substantially, including verification of potential to provide savings, retrofit isolation, or 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 or water 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 flow measurement.	Focused on specific building component or system. Amount and frequency of data vary widely between projects.	Energy or water audit. Identify and solve operation and maintenance, indoor air quality, or system problems. Provide input for models. Building commissioning.

Energy or Water End Use Assessment

Energy or water end use assessment projects typically focus on individual energy or water 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 or water use. Examples of this approach include detailed utility load research efforts, energy or water audits, 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 particular equipment or technologies that affect building energy or water use, such as envelope retrofit measures, major end use system loads or savings from retrofits (e.g., lighting, plumbing fixtures), 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 indoor/outdoor 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 improvements to energy/water efficiency, it is preferable to measure in situ performance. Although manufacturers and laboratory performance measurements can provide excellent data for sizing and selecting equipment, installed performance can differ significantly from that at design conditions. The project scope may include reliability, maintenance, design, energy or water efficiency, sizing, and environmental effects (Phelan et al. 1997a, 1997b).

Savings Measurement and Verification (M&V)

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

- Ensure that appropriate data are available, including pre-retrofit 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 or water savings
- Take post-retrofit measurements
- Estimate the savings achieved

Proper assessment of a retrofit involves comparing before and after energy or water use, and adjusting for all non-retrofit changes that affected that 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. To do so, relationships must be found between and these factors and energy or water use. 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 a given relationship. The need for accuracy 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 assumption. 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*).

Building Operation and Diagnostics

Diagnostic projects measure physical and operating parameters that determine the energy or water use of buildings and systems. Usually, the project goal is to determine the cause of problems, model or improve energy or water performance of a building or system(s), 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 or water diagnostic for buildings is determining rate of use or demand for a specific period, ranging from 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 procedures are used for energy and water measurements in residential (particularly single-family) buildings. 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); (3) infrared thermography to locate thermal defects in the building envelope and other methods to determine overall building envelope parameters (Subbarao 1988); and (4) faucet and shower flow meter bags.

Energy and water 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, flow meter bags, 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, identify plumbing leaks, and measure air leakage between apartments.

Diagnostic techniques have also been created to measure the overall airtightness of office building envelopes and the thermal performance of walls (Armstrong et al. 2001; Persily et al. 1988; Sellers et al. 2004). Practicing engineers also use a host of monitoring techniques to aid in diagnostics and analysis of equipment energy performance. Portable data loggers are often used to collect time-synchronized distributed data, allowing multiple data sets (e.g., 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 or water management programs (see [Chapter 37](#)). Long-term diagnostic measurements support 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 and water management efforts. Designers should consider providing permanent or portable check metering of major electrical loads and plumbing fixtures in new building designs. Building automation systems also can be used to collect the data required for diagnostics. The same concept can be extended to fuel and thermal energy use.

2. SMALL PROJECTS

Most metering projects are done on a small scale, and the project steps described in this chapter are simplified and compacted. This section briefly describes how to apply the information in this chapter to a small project.

Small projects are potentially impacted by the issues described here, but if only a small group of people are involved, they can choose what to address and how to handle the project requirements. [Table 2](#) relates small-project approaches to the material in this chapter.

How to Use This Chapter for Small Projects

1. Skim through the chapter and make a few notes on items that may apply for the project in question.
2. Generate a brief project plan to ensure major issues that could cause problems are not overlooked.
3. Generate a brief checklist from the item notes for final check-off during or at the end of project.
4. Clarify what building or site characteristics data may be needed, and be sure to collect those data.
5. Analyze data from the start, to make sure there are no quality or data issues.
6. Consider whether any data should be made available to others at the end of the project, and if so, develop a data format for exchange.
7. Skim through the chapter again when the report is being prepared to gather ideas about what to include in the report.

3. PROTOCOLS FOR PERFORMANCE MONITORING

ASHRAE (2010) gives protocols for performance monitoring of commercial buildings (energy, water, thermal comfort, indoor air quality, lighting, and acoustics) at three levels (basic, intermediate, and advanced). These protocols apply to both retrofit and new building projects and identify what to measure, how to measure (instrumentation and spatial resolution), and how often to measure. Implementation of these protocols for the same six elements, at three levels (basic evaluation, diagnostic measurement, and advanced analysis) is discussed in ASHRAE (2012). Examples of procedures (protocols) for evaluating **energy or water savings** for projects involving retrofit of existing building systems are presented here. These protocols should also be useful to those interested in more general building energy or water monitoring.

Table 2 Comparison of Small Projects to Overall Methodology

Project Characteristic	Small Project Approach	Overall Methodology Coverage
Project problem areas	<ul style="list-style-type: none">• Project goals and resources are iteratively evaluated in short time. Only one to possibly a few people involved. Small group allows more informal procedures and high interaction as needed.• Data products loosely defined. Data collection starts. Initial and ongoing analysis indicates any data management or quality control issues.• Data products refined over time as needed, based on analysis.• Accuracy evaluated on the fly as data are collected.• Commitment is to finish the work.• Advice still sought where needed.	Project goals, project costs and resources, data products, data management, data quality control, commitment, accuracy requirements, advice.

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Building and occupant characteristics	Typically, only one to a few buildings included; work is reasonably local. Characteristic data collected on site, at convenience of project person(s), depending on project location. Return trips likely needed for simplified data collection approach; supporting data can be collected on return trips.	Fairly extensive data structure (e.g., a characteristic database) and definition of levels of detail may be needed to handle possibly many buildings and improve ability to report results. With many buildings, only one trip per building may be acceptable.	
Project design	Project personnel usually know what they want to measure and report, and may not want to be confused by complex approach in this chapter. Knowledge of experimental approaches may also be understood minimally but still applied successfully, without specific declaration, to small project.	Three higher-level general approaches: (1) fewer buildings or systems with more detailed measurements, (2) many buildings or systems with less detailed measurements, or (3) many buildings or systems with more detailed measurements. Six major experimental design approaches: on/off, before/after, test/reference, simulated occupancy, nonexperimental reference, engineering field test.	
Reporting	Reporting is informal to somewhat formal (more like straightforward engineering project than research project). Reported results are often minimal but provide key information.	Research project report is likely required, possibly hundreds of pages long, with multiple appendices. Extensive databases likely generated and must be quality checked and corrected for use by others. Data user access procedures may have to be developed. Databases must be maintained over years in many cases and must be well documented. Extensive research results may have been generated and should be reported. For example, Fracastoro and Lyberg (1983) discussion of guiding principles for residential projects is 300 pages long.	

Building monitoring has been significantly simplified and made more professional in recent years by the development of these 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 monitoring 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 parameters are defined carefully to ensure consistency and comparability between experiments. Discrepancies between predicted and actual performance, as measured by the energy or water bills, 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 monitoring duration. Utility bill analysis generally requires a full season of pre- and post-retrofit 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 that can be used to study additional issues. See [Table 3](#) for details. Szydlowski and Diamond (1989) developed a similar method for multifamily buildings.

Table 3 Data Parameters for Residential Retrofit Monitoring

	Recording Period	
	Minimum	Optional
<i>Basic Parameters</i>		
House description		Once
Space-conditioning system description		Once
Entrance interview information		Once
Exit interview information		Once
Pre- and post-retrofit 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
<i>Optional Parameters</i>		
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).

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.

Data parameters in this protocol have been grouped into four data sets: basic parameters, occupant behavior, microclimate, and distribution system (Table 3). 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, measurement frequency, and expected ranges for all time-sequential parameters (Table 4). 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.

Table 4 Time-Sequential Parameters for Residential Retrofit Monitoring

Data Parameter	Accuracy ^a Range		Stored Value per Recording Period	Scan Rate ^b	
				Option 1	Option 2
Basic Parameters					
Heating/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 Retrofit Monitoring

Several related guidelines have been created for evaluating **retrofit savings (measurement and verification [M&V])**. ASHRAE *Guideline* 14-2014 provides methods for effectively and reliably measuring the energy, water and demand savings due to building improvement projects. The guideline defines a minimum acceptable level of performance in measuring energy, water, and demand savings from conservation measures in residential, commercial, or industrial buildings. These measurements can serve as the basis for commercial transactions between energy services providers and customers who rely on measured energy or water 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.

Table 5 Performance Data Requirements of 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	Daily	Same as billing data length
	—or— Integrated averages	Same as for submetered data but not longer than daily	—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	Daily	Same as billing data length
	—or— Integrated averages		

The Federal Energy Management Program (FEMP) has produced guidelines specific to federal projects, which include many procedures applicable to calculating retrofit savings in nonfederal buildings (FEMP 2015).

On a more detailed level, ASHRAE research project RP-827 resulted in separate guidelines for in situ testing of chillers, fans, and pumps to evaluate installed energy efficiency (Phelan et al. 1996, 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, and many monitoring source books are in circulation.

Finally, MacDonald et al. (1989) developed a protocol for field monitoring studies of energy improvements (retrofits) for commercial buildings. 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 or water performance. The necessary performance data, including identification of a minimum data set, are outlined in [Table 5](#).

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
- Highlighting inefficient or improper operation of equipment
- Providing data that can be useful in determining benefits of alternative operating strategies or replacement equipment
- Evaluating costs of operation for extending occupancy hours for special conditions or event
- Demonstrating effects of poor maintenance or identifying when maintenance procedures are not followed
- Diagnosing and fixing comfort and other space condition problems
- Diagnosing power quality problems
- Submetering tenants
- Verifying/improving savings of a performance contract
- Maintaining persistence of energy or water savings

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

Guidance on energy monitoring to determine energy savings for new construction design modifications is available in the Uniform Methods Project (NREL 2014). 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 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) or BAS for monitoring is particularly appropriate in new construction. These systems can monitor, calculate, and record system status, water use, energy use at the main meter or of particular end-use systems, demand, and hours of operation; as well as start and stop building systems, control lighting, and report alarms when systems do not operate 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).

4. COMMON MONITORING ISSUES

Field monitoring projects require effective management of various professional skills. Project staff must understand the building systems being examined, quality control of data, 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 hardware selection 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 approaches different 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 at an early stage to assess with certainty the cost of an anticipated project, 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 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.

Data Quality Control. It is also important to validate the quality and plausibility of data before use. Failure to use some type of quality control often results in data errors and invalid results.

Commitment. Many projects require long-term commitment of personnel and resources. Project success depends on long-term, daily attention to detail and 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 trade-offs must usually be made between cost and accuracy, this process is often iterative. It is further complicated by a large number of independent variables (e.g., occupants, operating modes) and the stochastic nature of many variables (e.g., 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* 14-2014).
- 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 because of 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.
- Occupancy surveys are generally used as subjective measures to assess indoor environmental quality (thermal comfort, IAQ, lighting, acoustics). Surveys such as those of the Center for the Built Environment at the University of California at Berkeley (CBE 2022) or the Minnesota State Safety and Industrial Hygiene Unit (2000), can be administered in paper or electronic form, and provide comparison of sampled results with those of peer buildings. The measurements can be taken over time to determine any changes in occupant satisfaction.

Data Analysis and Reporting

For most projects, the collected data must be analyzed and reported. 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.

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

5. 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, such as when desired levels of instrumentation exceed the resources available, adjustments are needed. Planning should identify and resolve any trade-offs necessary to execute the project in 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.

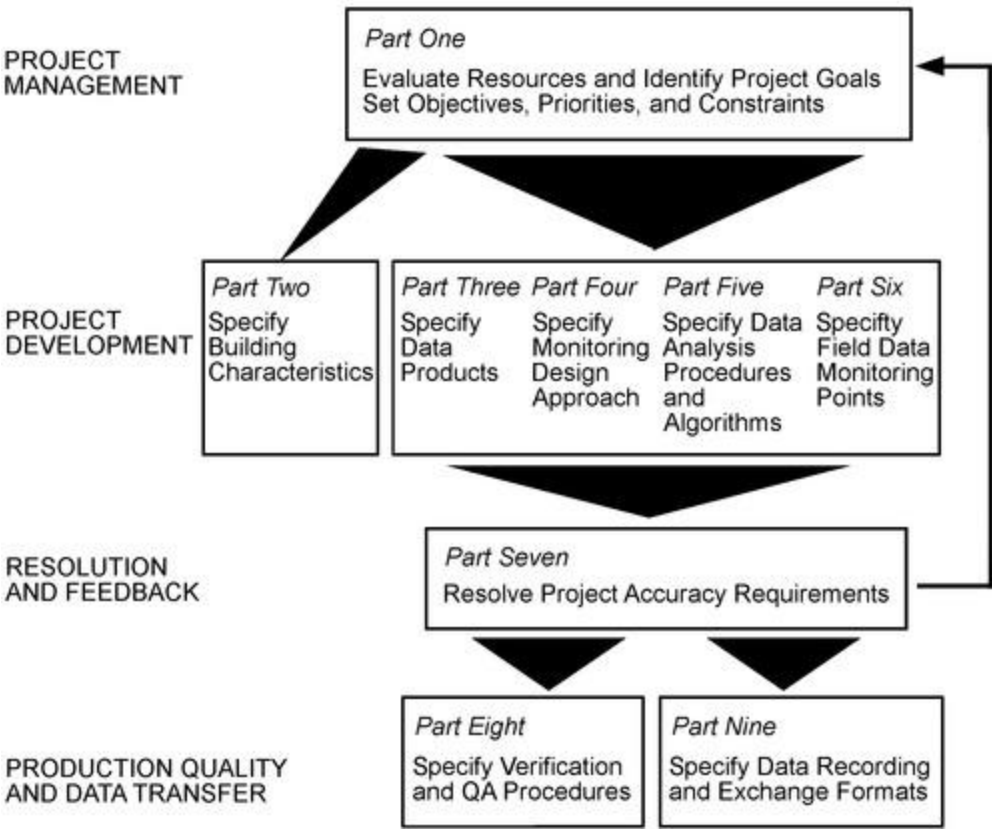


Figure 1. Methodology for Designing Field Monitoring Projects

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. This report can be a useful part of an overall project plan that may document other important project information, such as resources to be used, schedule, etc.

Part One: Identify Project Objectives, Resources, and Constraints

Start with a clear understanding of the decision or action that the project will inform. 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 project constraints defined and considered. Trade-offs on budget and objectives require that priorities be established.

Even if a project is not research-oriented, it is attempting to obtain information, which can be expressed in the form of questions. Research questions can have varying scopes and levels of detail, addressing entire systems or specific components. Examples of research questions include

- **Measurement and verification:** Have contractors fulfilled their responsibilities of installing equipment and improving systems to achieve the agreed-upon energy or water savings?
- **Classes of buildings:** How much energy or water has been saved by using the building construction/performance standard mandated in the jurisdiction?
- **Particular buildings:** Has a lapse in building maintenance caused energy or water 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 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 it becomes to identify required data.

Part Two: Specify Building and Occupant Characteristics

Measured energy or water data will not be meaningful 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, especially lighting
- Type and quantity of potable water fixtures
- Any building changes that occur during the monitoring project
- Entrance interview information focusing on energy or water-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 not to merely 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** (scope, 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 are necessary to achieve desired results; assurance should be given that the resources needed to analyze the data, once collected, are available. 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 trade-offs 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 Design of Monitoring

A general monitoring design must be developed that defines three interacting factors: the number of buildings in 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 monitoring methods, from retrofit verification to retrofit isolation (ASHRAE *Guideline* 14-2014; FEMP 2015). Some monitoring approaches are better suited than others to larger numbers of buildings.

Specifying the 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 (e.g., 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 number of buildings in the experiment is fixed at one. However, for other monitoring applications, such as drawing conclusions about effects in a sample population of buildings, some selection 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 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 adjust for some outside influences. For more information, see Box (1978), Fracastoro and Lyberg (1983), and Hirst and Reed (1991). Projects can also use more complex, multilevel measurement and modeling approaches to handle an array of technologies or to improve confidence in results (Hughes and Shonder 1998).

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

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, 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* 14-2014; FEMP 2015; IPMVP 2014).

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).

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. On-period consumption is then compared to off-period consumption (Cohen et al. 1987; Woller 1989).

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 held constant 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 representative standard (peer) 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* 14-2014; FEMP 2015).

Engineering Field Test. When an experiment focuses on testing a particular piece of equipment, actual (in situ) 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 or water usage. Because energy consumption of mechanical equipment is significantly affected by the system control strategy testing procedures 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 6](#) (Fracastoro and Lyberg 1983). Combining monitoring design choices can be successful (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?
- 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 not held constant or accounted for.
- Are critical baseline energy or water performance data available? 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 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 is 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

- Determine the independent variables and analysis constants to be measured in the field (e.g., fan power, lighting and receptacle power, indoor air temperature).
- Develop engineering calculations and equations (algorithms) necessary to convert field data to end products: this may include 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 may be assembled into hourly data streams to match utility billing data.

Table 6 Advantages and Disadvantages of Common Experimental Approaches

Mode	Advantages	Disadvantages
Before/after	No reference building required. Same occupants implies smaller occupant variations. Modeling processes are 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 are mostly identical before/after. Most occupancy changes are 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 from 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 product of interest. Minimal number of buildings required. Same occupants during test.	Extensive instrumentation of product processes required. Models required to extrapolate to other buildings and climates. Occupancy effects not determined.

Source: Partially based on Fracastoro and Lyberg (1983).

Determine proper National Institute of Standards and Technology (NIST)-traceable calibration standards for each sensor type to be used. For details, see the references in ASHRAE *Guideline* 14-2014 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, requiring compromise.

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

[Chapter 19 of the 2021 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 7](#) provides a guide to selecting an analysis method. The error quotations are rough estimates for a single-building scenario.

Empirical Methods. Although analysis methods based on measured data are the simplest, they can have large uncertainty and may 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, much of which is described in ASHRAE *Standard* 100-2015. Questions about building performance relative to other buildings are based on comparing certain performance indices between the building and an appropriate (peer) reference. The ENERGY STAR tools (www.energystar.gov) are probably the best-known performance comparison tools. The ASHRAE Building Energy Quotient (Building EQ) tool has also been developed to not just provide performance comparison (benchmarking), but also streamline the energy audit process to include improvement measures in the report generated from Building EQ.

For commercial buildings, the most common comparison index is the **energy utilization index (EUI)**, which is annual consumption, either by fuel type or summed over all fuel types, divided by the gross floor area (see MacDonald and Wasserman [1989] for a discussion of indices). 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, number of workers in a building, number and type of computers in a building, and HVAC systems. 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 (CBECS) database (summarized in [Chapter 37](#)) has been used to develop ENERGY STAR and Building EQ energy use benchmarking methods for several building types in the United States. Many of the building tools use current CBECS survey data. However, tools that rely on ASHRAE *Standard* 90.1-2019 using 2003 CBECS data as a fixed baseline may also use 2003 data. Building EQ is an example of such a tool (Najafi et al 2022). Building types covered as of June 2009 include the following.

- Offices (general offices, financial centers, bank branches, and courthouses)
- K-12 schools
- Supermarkets/grocery stores
- Hospitals (acute care and children's)
- Medical offices and clinics
- Hotels/motels
- Residence halls/dormitories
- Retail stores
- Warehouses (refrigerated and nonrefrigerated)

For some of these building types, some secondary spaces are allowed:

- Computer data centers
- Garages and parking lots
- Swimming pools

Table 7 Whole-Building Analysis Guidelines

Project Goal	Class of Method		
	Empirical (Billing Data)*	Time-Integrated Model*	Dynamic Model
Building evaluation	Yes, but expect monthly 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 outdoor temperature approaches balance temperature.

Initial work in this area covered only electricity use for office buildings (Sharp 1996), but the methods have been extended to cover all fuels for the listed building types and water. Results show that electricity use of office buildings is most significantly explained by the number of workers in the building, number of computers, whether the building is owner-occupied, and number of operating hours each week. Only a subset of these parameters might be used to determine a benchmark within a specific census division. ENERGY STAR documentation on current tools and the performance normalization factors for a range of building types can be found at www.energystar.gov/buildings.

Simple empirical methods applied to retrofit applications should include at least some periods of data on daily energy or water 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). ASHRAE (2012) gives best-practice protocols for measurements at different time periods.

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-and-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, as often embodied in hour-by-hour simulation programs. 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 normalization 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). Simulation modeling results used for design of new buildings may not cover all energy used in a building and thus could be difficult to compare with empirical data.

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 outdoor temperature, internal gains, and internal temperature (ASHRAE 2002; Fels 1986; Haberl and Claridge 1987). This type of calibrated model 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 analyze 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 indoor/outdoor temperature difference data in certain models. Estimation errors result if these parameters are independently time-integrated and then used to calculate air infiltration. These 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 lead to error. These 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 indoor/outdoor temperature differences. Billing data analysis yields little of interest when internal gains are large compared to envelope loads, as in large commercial buildings and industrial applications. Daily, weekly, and monthly whole-building heating season consumption integration steps can

been used (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 in the building energy balance, outdoor 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 annual chiller 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 measured to produce required data. The analysis method determines the data to be measured. The simplest methods require no on-site 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 equipment is installed.

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

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, such as those recommended in ASHRAE (2010), 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

- Evaluating 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.
- Considering local setup and testing of complex data acquisition systems that are to be installed in the field.
- Avoiding unproven data acquisition equipment (Sparks et al. 1992). Untested equipment, even if donated, may not be a good value.

- Considering costs and benefits of remote data interrogation and programming.
- Evaluating quality and reliability of data loggers and instrumentation; these issues may be more important than cost, particularly when data acquisition sites are distant.
- Verifying vendor claims by calling references or obtaining performance guarantees.
- Considering portable battery-powered data loggers in lieu of hard-wired 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 that 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 8](#). Some typical concerns for selecting data acquisition hardware are outlined in [Table 9](#). 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). Some measurements that are more difficult to obtain accurately because of instrumentation limitations are summarized in [Table 10](#).

Table 8 General Characteristics of Data Acquisition System (DAS)

Types of DAS	Typical Use	Typical Data Retrieval	Comments
Manual readings	Total energy or water use	Monthly or daily written logs	Human factors may affect accuracy and reading period. Data must be manually entered for computer analysis.
Pulse counter, solid state (1, 4, or 8 channels)	Total energy or water use (some end use)	Polled by telephone to mainframe or minicomputer	Computer hardware and software are 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 thousands of 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 9 Practical Concerns for Selecting and Using Data Acquisition Hardware

Components	Field Application Concerns
Data logger unit and peripherals	<ul style="list-style-type: none"> • Select equipment for field application. Flexible or adaptable input capabilities desirable. • Equipment should store data electronically for easy transfer to a computer.

	<ul style="list-style-type: none"> • Remote programming capability should be available to minimize on-site software modifications. • Avoid equipment with cooling fans. • Use high-quality, reliable communication devices or methods. • Make sure logger/computer and communication reset after power outage.
Cabling and interconnection hardware	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Use rugged, reliable sensors 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 or power supply, if possible. • Calibrate sensors and recalibrate periodically. • When possible, use redundant channels to cross-check critical channels that can drift.

Safety must be considered in equipment selection and installation. Installation teams of two or more individuals 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.

Table 10 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 (especially for steam flow). Moving parts prone to failure. Pipe size must be verified before 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 transducers (CTs) often marked incorrectly, problems with shunt resistors and CT output. Devices should be checked before installation.

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, preferably with a NIST-traceable calibration procedure. They should be checked periodically for drift, recalibrated, and then post-calibrated 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 indoor 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. For temperature or pitot tube flow measurements the location must be sufficiently downstream of louvers, filters, and pipe turns to obtain accurate results.

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 indoor and outdoor 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 (e.g., 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 heating or cooling

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 Project Data 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 outdoor dry-bulb temperature)

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

Basic Concepts. Uncertainty can be better understood in terms of confidence limits, which 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 observations 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 X' provides a direct indication of the confidence limits. Thus the "true" mean value X' of the random variable is bounded as follows:

$$X' \pm (t_{\alpha/2, n-1} \sqrt{\sigma^2/n}) \quad (1)$$

where

td>

α	=	level of significance
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 removed by calibration, (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. 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 $\sigma^2(b_m, \varepsilon_m) = \sigma^2(b_m) + \sigma^2(\varepsilon_m)$

$$\sigma_{meas}^2(b_m, \varepsilon_m) = \sigma^2(b_m) + \sigma^2(\varepsilon_m) \quad (2)$$

For further information on uncertainty, see [Chapter 37 of the 2021 ASHRAE Handbook—Fundamentals](#). For more information on uncertainty calculation methods related specifically to building energy savings monitoring, see ASHRAE *Guideline* 14-2014, 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 random errors, the 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 remove them through calibration 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 regression variable (Box 1978). Measurement error is inherently included 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 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 monitoring to average out stochastic variations
- Increasing the number of buildings tested (sample size)

On the other hand, if simulations or estimates indicate that the expected bias in the final data product 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 in 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 trade-off, 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

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 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.

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 due to 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 data quality after collection.
- Perform initial analysis of 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 11](#): 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 acceptable performance quality.

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.

Table 11 Quality Assurance Elements

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

Part Nine: Specify Recording and Data Exchange Formats

This step specifies the formats in which data are 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 storage, 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 12](#)). Because these guidelines apply to general data, models, programs, and other types of information, items listed in [Table 12](#) may not apply to every case.
- Provide documentation of transfer media, including the computer operating system, software used to create the files, media format (e.g., ASCII, application-specific), and media characteristics (note that many CD-ROM formats exist, some of which are proprietary and not widely used, so care should be taken to use commonly available methods).
- 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 12 Documentation Included with Computer Data to Be Transferred

1. Title and/or acronym
2. Contact person (name, address, phone number)
3. Description of file (file format, 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, variable formats)
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, such as
 - 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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