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Procedure for Measuring and Reporting Commercial Building Energy Performance

D. Barley, M. Deru, S. Pless, and P. Torcellini

Technical Report
NREL/TP-550-38601
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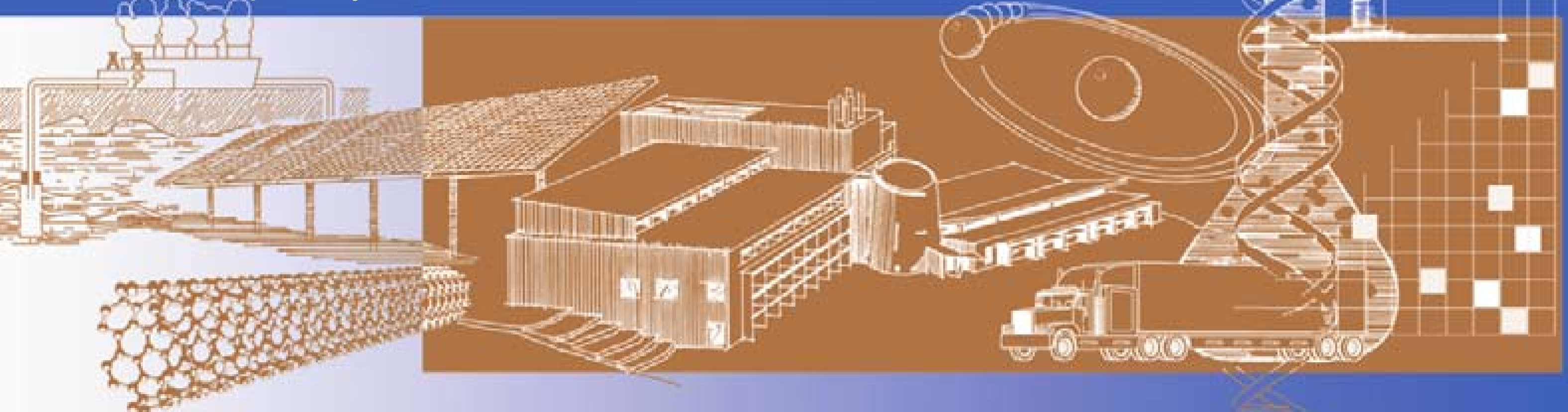

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Prepared under Task No. BEC3.3003

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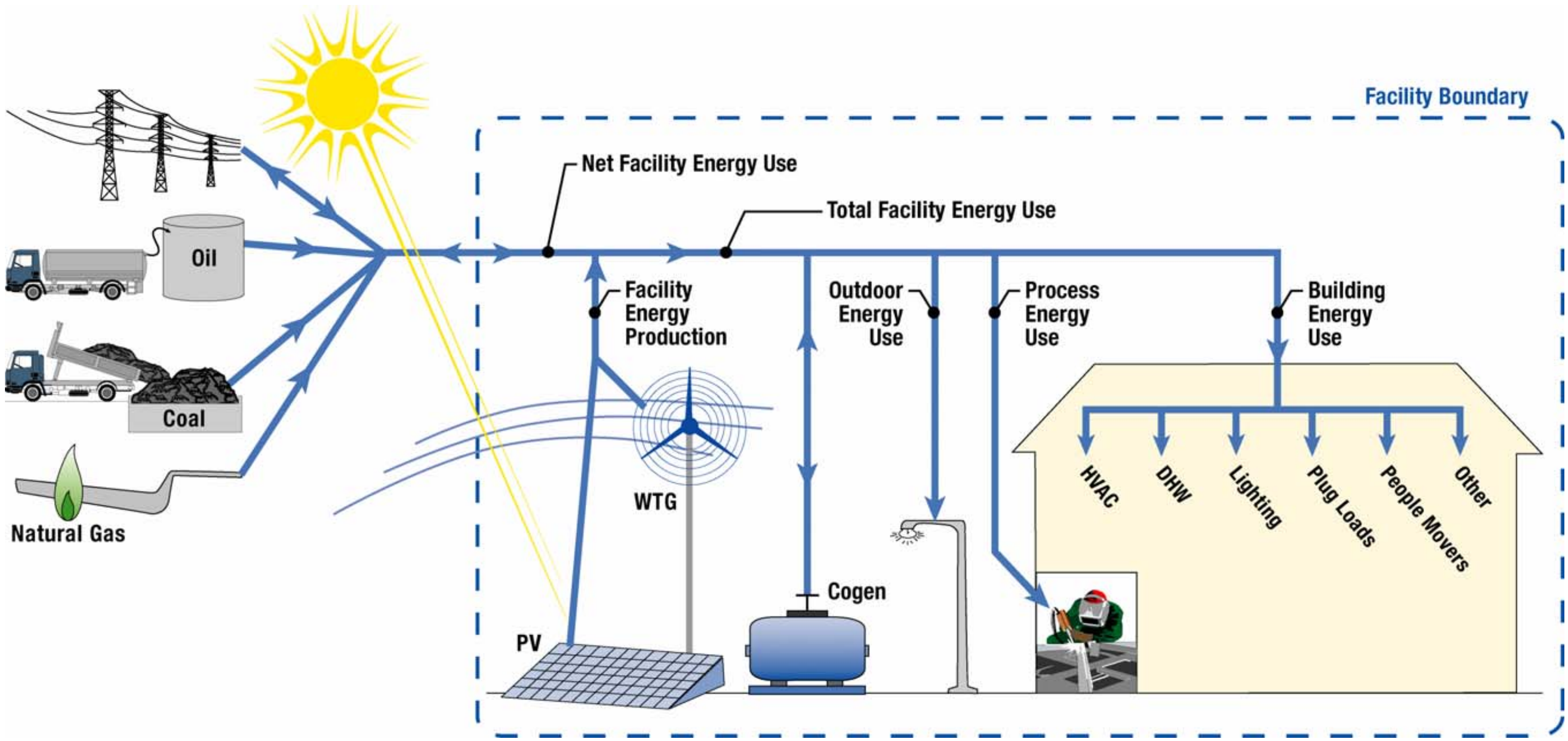

Energy flow diagram providing an overview of this procedure
Figure 4-1 shows a more detailed diagram of the relationships among metrics.

Acknowledgments

The authors want to thank Sheila Hayter of NREL for her valuable contributions to this project and the following individuals for reviewing this document: David Hansen (DOE), John Ryan (DOE), Drury Crawley (DOE), Terry Logee (DOE), Otto Van Geet (NREL), Michael McCabe (Navigant Consulting, Inc.), and Ed Hancock (Mountain Energy Partnership).

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Quick Reference Guide

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Foreword

People measure and analyze the energy performance of buildings for many reasons. Comparisons of energy use may be made among nations, regions, individual buildings, or systems within a building. Policy makers, owners, designers, operators, raters, and researchers use energy performance data. Many tools (or approaches) have been developed to analyze energy performance in different ways, at different levels of effort and precision, and at different stages in the life of a building. Each tool quantifies the building energy performance to fit the users' needs. However, methods and metrics are often inconsistent with each other. In addition, performance numbers may be misrepresented or misused to predict energy savings beyond the accuracy of the numbers.

The Performance Metrics Project is a U.S. Department of Energy commercial buildings research activity whose goal is to standardize the measurement and characterization of building energy performance. Its main products are clearly defined energy performance metrics and standard procedures for determining the performance metrics; its intents are to define common language and to create standards that produce consistent results independently of the user. Therefore, the terms and techniques are clearly defined with little room for interpretation. The more opportunity there is for interpretation, the higher the probability for disparity and "gaming" of the results. These procedures focus on reporting absolute numbers and not on comparisons of energy performance. Benchmarks are included only where well-established values apply. However, benchmarking of results by others can be improved be using the clearly defined absolute metrics determined by these procedures.

Numerous other documents outline procedures for analyzing building energy performance (see references in Section 8). Some procedures are general and tend to outline the stages of project planning, management, and execution; they do not encompass the level of detail necessary to standardize specific measurements among buildings. On the other hand, the procedures that do encompass the necessary level of detail are not general enough to provide a standard basis of comparison among buildings. Stewart et al. (1984), in reviewing numerous energy audit procedures, commented:

> Unfortunately, in the rush to account for energy usage, no cohesive pattern of auditing procedures was developed. Instead, a plethora of forms and procedures was prepared, often just for specific tasks. The result is the inability to compare the results of one audit to another with any sense of confidence.

Also, Misuriello (1987) commented, "The diverse nature of monitoring projects realistically precludes a universal protocol applicable to all monitoring efforts."

The Performance Metrics Project attempts to build on this body of work and resolve differences among the various approaches. The project has worked to address the following issues that have been problems with performance monitoring in the past:

- *Standardization:* Standard performance metrics provide a consistent basis for comparing energy performance among buildings.
- *Versatility:* The analysis is customized to the facility boundaries, energy configuration, analysis goals, and analysis budget that apply to a given project.
- *Economy of Effort:* The data collection is carefully matched to the goals of the analysis and the study questions to avoid the common pitfalls of too few or too many data.

Each procedure in this series outlines a measurement protocol that helps to quantify standard performance metrics. These documents are intended for building energy analysts and technicians who design, install, and operate data acquisition systems, and who analyze and report building energy performance data. In addition, the Metric Definitions in Section 4 of each procedure may be useful to others who interpret and apply such data.

Two levels of effort are outlined in these procedures to meet the needs of different users and to address the goals of *versatility* and *economy of effort* in performance monitoring. In Tier 1, utility bills and other rapid, inexpensive means of data gathering are used to determine monthly and annual purchased energy, electrical demand, facility energy production, and related metrics. In Tier 2, submetering and an automated data acquisition system are used to determine hourly or subhourly time-series data, itemized by end use. Tier 1 analysis compares annual *facility* energy performance. A Tier 1 analysis may or may not describe *building* energy performance, depending on other energy uses at the facility. For end-use energy totals or predictions of savings from changes in systems,[1] a Tier 2 analysis must be performed. A Tier 2 analysis can require a substantial effort, and the benefits of this detailed study should be weighed against the associated costs. With either Tier 1 or Tier 2, performance is measured for a period of 1 year to determine seasonal trends and annual totals.

[1] Although this procedure does not predict savings from proposed changes, the results of a Tier 2 analysis could be useful for that purpose in a subsequent analysis.

Section 1 – Purpose

The purpose of this procedure is to establish a standard method for monitoring and reporting on the energy performance of commercial buildings.

Section 2 – Scope

2.1 – Overview

This procedure is intended to provide a standard method for measuring and characterizing the energy performance of commercial buildings. The procedure determines the energy consumption, electrical energy demand, and on-site energy production in existing commercial buildings of all types. The performance metrics determined here may be compared against benchmarks to evaluate performance and verify that performance targets have been achieved. Uses may include:

- Compare performance with the design intent
- Compare performance with other buildings
- Evaluate building performance rating systems
- Perform economic analysis of energy-efficient strategies in buildings
- Establish long-term performance records that enable maintenance staff to monitor trends in energy performance.

The procedure is divided into two tiers to differentiate the resolution of the results and the amount of effort typically required to complete the procedure. Tier 1 gives monthly and annual results for the facility as a whole, based primarily on utility meter readings. Tier 2 yields time-series results (typically 15- or 60-min data, which should correspond to the electrical demand billing scheme, if applicable), in addition to monthly and annual results, itemized by type of end use, based on submetering and a data acquisition system (DAS). With either Tier 1 or Tier 2, performance is measured for a period of 1 year to determine seasonal trends and annual totals. Typically, for a Tier 1 analysis of an existing building, such data have already been recorded on utility bills, so the procedure may be completed in a matter of days. For a Tier 1 analysis of a newly completed building, a 1-year waiting period will be necessary to collect the data. For a Tier 2 analysis, the measurement (which will take at least 1 year to complete) is part of the procedure.

This procedure does not include computer simulation analysis of proposed buildings. A procedure for simulation should provide instructions regarding the choice of software, time step, assumed building operating conditions, weather data, and many other modeling parameters. Without guidelines for these choices, results may vary significantly. However, it may prove useful to apply the *metrics* defined here in a simulation analysis to facilitate a subsequent comparison of measured performance to simulated performance.

This procedure includes definitions of the performance metrics obtained,[2] detailed steps for quantifying performance, and a list of suggested monitoring equipment (Appendix B).

2.2 – What This Procedure Does

This procedure accounts for all forms of purchased energy, including electricity, oil, gas, coal, liquefied propane gas (LPG), district heat, and other. It also accounts for all forms of on-site energy conversion including fuel cells, fueled generators, and cogeneration units and on-site energy production, including photovoltaic (PV), wind, geothermal, and solar thermal. This procedure applies to facilities with on-site

[2] Additional, user-defined metrics may also be included in the analysis. See Section 4 and Section 6.3, Step II.A.

storage of fuel, such as oil or LPG, provided that the fuel use is metered as it is dispensed from storage. It also encompasses energy storage components such as batteries, flywheels, thermal storage media, and hydrogen storage. It encompasses all types of existing commercial buildings.

2.3 – What This Procedure Does Not Do

This procedure does not determine source energy consumption, although it does itemize energy consumption by energy type, so the results would be useful for that analysis. See *Source Energy and Emission Factors for Energy Use in Buildings* for more information (Deru and Torcellini 2005a) Natural energy flows such as passive solar heating, daylighting, natural ventilation, and heat generated by occupants are not measured or included in the energy totals. This procedure does not furnish diagnostic support to identify the reasons that systems do not perform as designed, nor does it give guidance on repair techniques. Methods for analyzing proposed buildings, such as computer simulation, are not presented here; however, these metric definitions may be used in such studies, for consistency and later comparison with actual data collected by this procedure. Energy-related metrics that are not included in this procedure include indoor relative humidity (RH), human comfort, water consumption, and condenser heat rejection. Finally, this procedure does not present a method for benchmarking performance based on any reference cases.

Section 3 – Definitions, Abbreviations, and Acronyms

3.1 – General

Terms, abbreviations, and acronyms defined in this section apply to this procedure. The names of performance metrics are defined in Section 4 and printed in **bold type** throughout this document. Terms, abbreviations, and acronyms not defined in either Section 3 or Section 4 are assumed to have their ordinary definitions in the context in which they are used, based on standard American English.

3.2 – Definitions

Annual

A period that consists of 12 consecutive months.

Data Acquisition System (DAS)

An automated data recording system that typically consists of a programmable data logger and numerous sensors and other transducers. It can record all the measurements needed to complete Tier 2 of this procedure. The recording interval should correspond to the applicable electrical demand-billing scheme, if applicable (typically 15- or 60-min data), so that the data enable demand-reduction strategies to be analyzed after the procedure is completed. (See also the definition of *time series*.) The system should be operated and the data collected for at least 1 year to allow seasonal trends and annual totals to be determined with this procedure.

Facility

A set of one or more buildings or outdoor applications, or both, that use energy and share a common utility meter. If there is a compelling reason to apply a different boundary to the analysis, that boundary and the reasons for using it should be clearly described in the report (see Appendix A, Table A-1, Item I.C).

Measure

To determine a quantity with a calibrated instrument. This term includes using previously measured data such as those shown on a utility bill or engineering log.

Metric

A standard definition of a measurable quantity. (See examples of performance metrics in Section 4.1.)

Month

A calendar month, or a utility billing period of similar duration. (See Section 6.4.1 for further details.)

Performance Metric

A standard definition of a measurable quantity that indicates some aspect of performance. Section 4 contains definitions of the specific performance metrics used in this procedure.

Procedure

A standard technique for determining one or more performance metrics, or a document (such as this one) that outlines such technique(s).

Source Energy

The sum of the energy consumed at a facility plus the energy required for extraction, conversion, and transmission of that energy to the facility.

Tier

A portion of a procedure that is categorized in terms of (1) the resolution of the results obtained and (2) the level of effort typically required to obtain the results. (See Section 6.2, Step I.D, for further explanation.) The particular performance metrics determined in each of the two tiers in this procedure are diagrammed in Section 4 and tabulated in Section 6.

Tier 1

The most basic level of a procedure, which yields the highest-level results. General characteristics of Tier 1 are that it (1) generally yields only monthly and annual results; (2) often requires only existing data, including utility bills, building drawings, and a physical examination (walk-through) of the building; and (3) is typically performed without installing additional metering equipment. In Tier 1 of this procedure, these means are used to determine and report monthly and annual purchased energy, electrical demand, facility energy production, and related metrics.

Tier 2

The advanced level of a procedure, which yields more detailed results. Most analysts who are interested in a detailed examination of a building's performance will perform a Tier 2 analysis. General characteristics of Tier 2 are that it (1) yields seasonal, daily, hourly, or subhourly (if appropriate) results; (2) yields results itemized by type of end use; and (3) requires new data to be recorded in addition to existing building data. Submetering and a DAS are generally employed.

Time Series

The data-recording interval that corresponds to the applicable electrical demand-billing scheme (typically 15- or 60-min data). If there is no applicable electrical demand-billing scheme, the recording interval should be based on any interest in using the data to analyze demand-reduction strategies.[3]

Year

365 consecutive days. (See Section 6.4.1 for further details.)

3.3 – Abbreviations

°C	degrees Celsius
°F	degrees Fahrenheit
Btu	British thermal unit
Btu/ft^2	British thermal units per square foot
J/m^2	Joules per square meter
kVA	kilovolt-amperes
kW	kilowatts
kWh	kilowatt-hours
kWh/ft^2	kilowatt-hours per square foot
kWh/m^2	kilowatt-hours per square meter

3.4 – Acronyms

AC	Alternating current
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
BAS	Building automation system
BEUI	**Building Energy Use Intensity** (defined in Section 4)
CDD	Cooling degree-days
CT	Current transformer
DAS	Data acquisition system (see definition in Section 3.2)
DC	Direct current
DHW	Domestic hot water (see definition of **DHW Energy Use** in Section 4)
EIA	Energy Information Administration
HDD	Heating degree-days
HVAC	Heating, ventilating, and air-conditioning
IESNA	Illuminating Engineering Society of North America
IPMVP	International Performance Measurement and Verification Protocol
LPG	Liquefied propane gas
NCDC	National Climatic Data Center
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
RH	Relative humidity
RMS	Root mean square
SOC	State of charge
TC	Thermocouple
WHM	Watt-hour meter
WTG	Wind turbine generator

[3] Synchronizing the analysis to the time base used by the utility company can be difficult. Thus, values of peak demand determined by monitoring may differ from those shown on the electric bill. Nonetheless, the data are useful for analyzing load management opportunities as an adjunct to this procedure.

Section 4 – Metrics Determined in This Procedure

The standard performance metrics determined in this procedure are defined in this section. Figure 4-1a shows an overview of the highest-level metrics. In addition, Figure 4-1b illustrates the relationships between most of the metrics in more detail, as well as the scope of the Tier 1 and Tier 2 analyses.[4] The names of these standard metrics are printed in **bold type** throughout this document. Section 6 outlines procedures for determining these metrics. For each metric, energy use or demand should be itemized by energy type: electricity, gas, fuel oil, coal, LPG, district heat, or specified other type.

Additional, user-defined metrics may be required by the goals of the analysis and the study questions. These may also be included in the measurement plan and the analysis (see Section 6.3, Step II.A). However, the names of any user-defined metrics should be clearly distinct from the names of the standard metrics, which are reserved for use as defined here.

4.1 – Metric Definitions

Air Distribution Energy Use

Fan energy used to move air in a building for heating, cooling, or ventilation. This includes all ducted air movement, all powered introduction of outside air, and all powered exhaust. It does not include a fan that is part of an indoor fan-coil unit used for heating or cooling within a single zone. See further explanation in Section 6.5.5.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Building Electrical Demand

Peak electrical demand of the electrical **Building Energy Use** during the month, as defined in the applicable electric utility rate structure.

Units: kW or kVA, corresponding to the electric utility rate structure

Reported as: Monthly values, annual maximum of monthly values (summer and winter seasonal values can also be reported) including date and time of peak demand values

Building Electrical Demand Intensity

= **Building Electrical Demand ÷ Functional Area**

Units: kW/ft^2, kW/m^2, kVA/ft^2, or kVA/m^2 corresponding to the electric utility rate structure

Reported as: Monthly values, annual maximum of monthly values (summer and winter seasonal values can also be reported)

[4] Some additional metrics, which are derived from those shown in Figure 4-1 or do not contribute to energy sums, are also defined in this section and included in a Tier 1 or Tier 2 analysis.

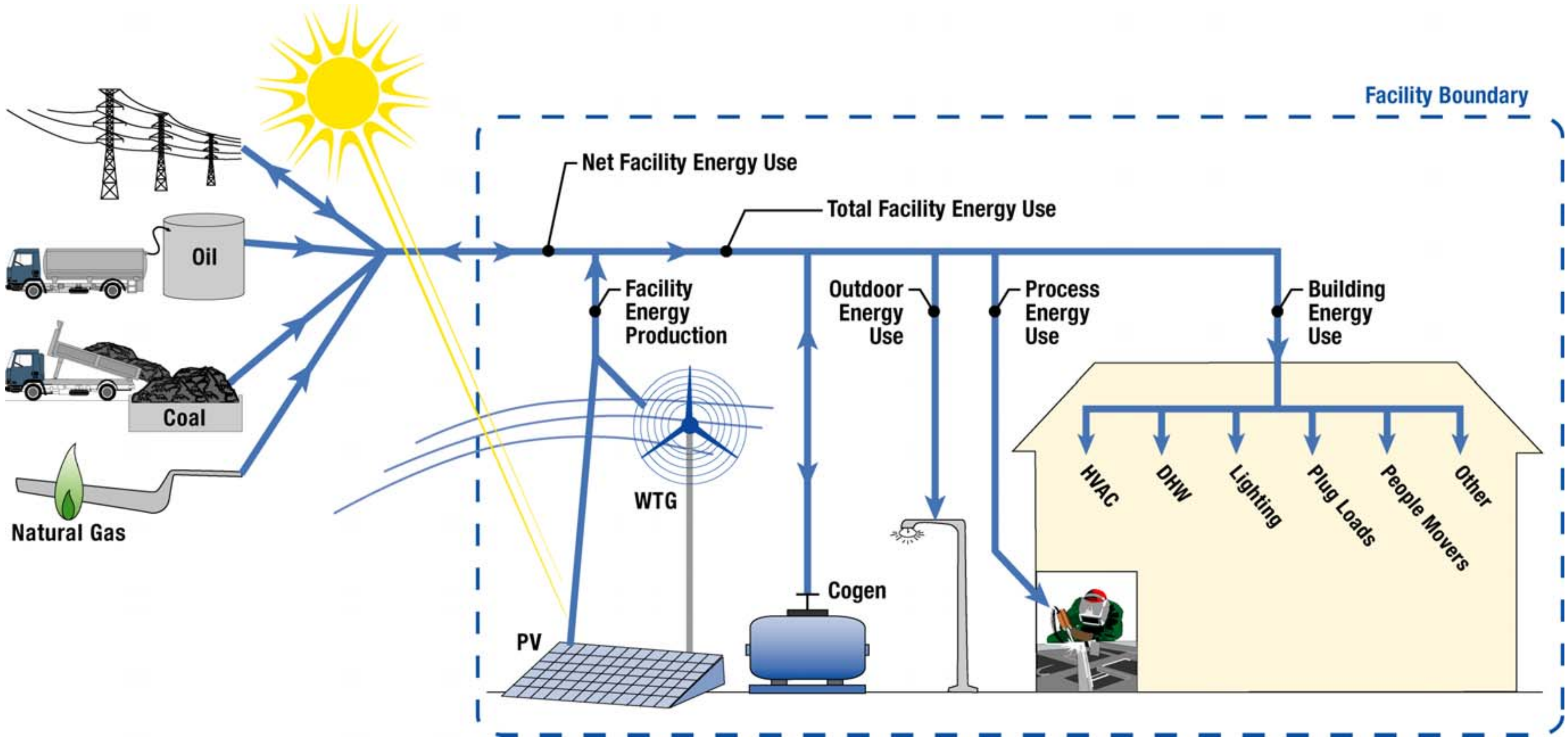
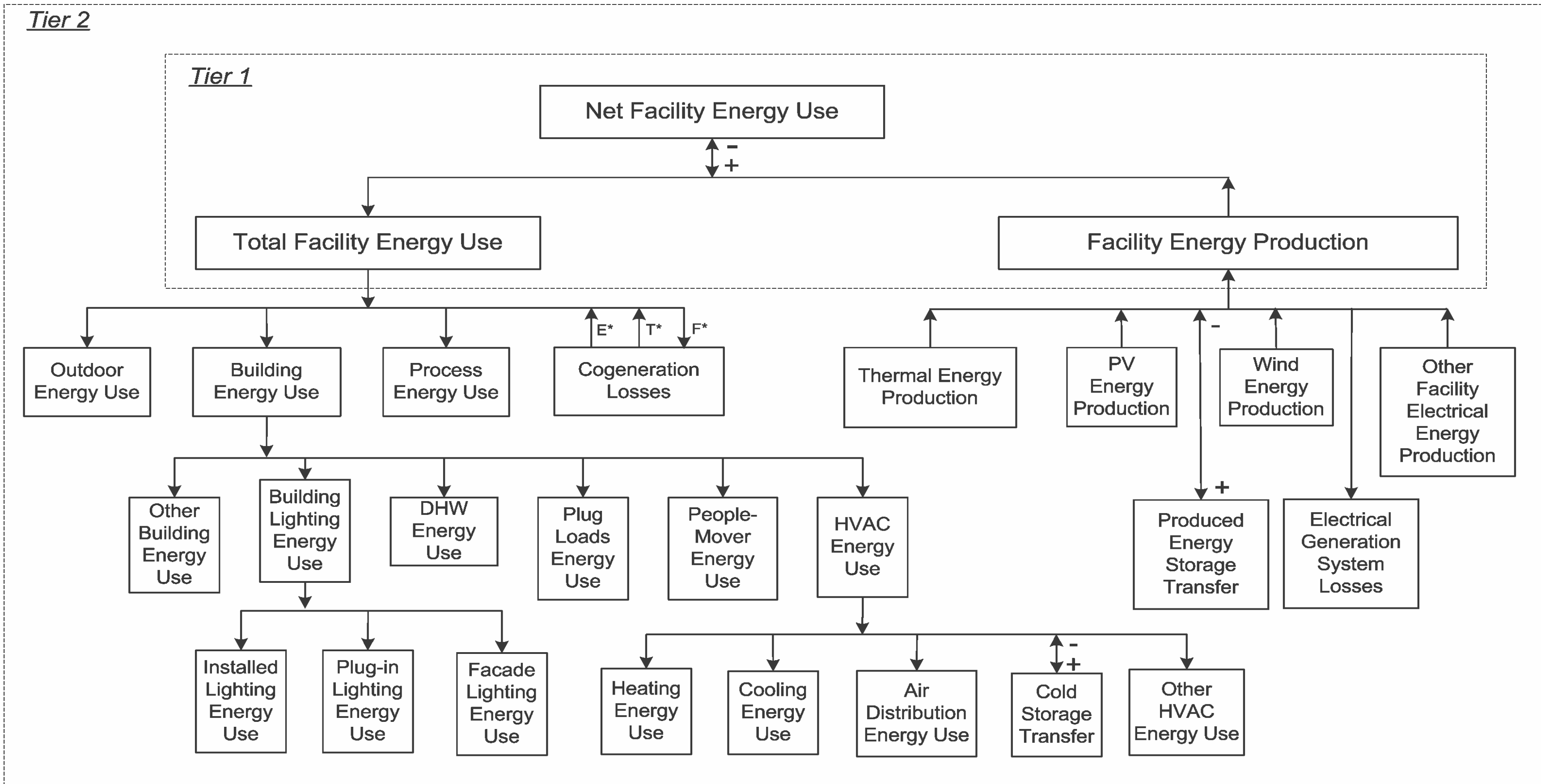


Figure 4-1a Energy flow diagram providing an overview of this procedure



*Note: E = Cogeneration Electrical Energy Output; T = Cogeneration Thermal Energy Output; F = Cogeneration Fuel Use

Figure 4-1b Diagram of related energy performance metric

Building Energy Use

Energy consumed in a building for heating, ventilating, and air conditioning (HVAC), indoor lighting, facade lighting, domestic hot water (DHW), plug loads, people movers, and other building energy use, excluding **Process Energy Use** and **Cogeneration Losses**. When a building has multiple functions (e.g., office, retail, laboratory, parking), the energy use may be itemized for each **Functional Area** for comparison to other buildings of the same types. Alternatively, the building may be analyzed as a whole and reported as a mixed-use building.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Building Energy Use Intensity (BEUI)

= **Building Energy Use** ÷ **Functional Area**

Units: kWh/ft^2, kWh/m^2, Btu/ft^2, or $Joules/m^2$

Reported as: annual value

Building Lighting Energy Use

= **Installed Lighting Energy Use** + **Plug-in Lighting Energy Use** + **Facade Lighting Energy Use**

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Building Purchased Energy Cost

Portion of the **Net Facility Purchased Energy Cost** that corresponds to the **Building Energy Use**

Units: $Currency_{Year}$ (see Section 7.3 for explanation)

Reported as: Monthly and annual values.

Building Purchased Energy Cost Intensity

= **Building Purchased Energy Cost** ÷ **Functional Area**

Units: $Currency_{Year}/ft^2$ or $Currency_{Year}/m^2$ (see Section 7.3 for explanation)

Reported as: annual value

Cogeneration Electrical Energy Output

Electrical energy produced by cogeneration equipment that is either (a) used at the facility in a way that offsets the consumption of purchased energy or other energy generated at the facility, or (b) exported from the facility and used elsewhere (e.g., electrical energy fed to the utility grid).

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period.

Cogeneration Fuel Use
Fuel consumed by cogeneration equipment.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period.

Cogeneration Losses

= **Cogeneration Fuel Use – Cogeneration Electrical Energy Output – Cogeneration Thermal Energy Output**

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period.

Cogeneration Thermal Energy Output
Thermal energy produced by cogeneration equipment that is either (a) used at the facility in a way that offsets the consumption of purchased energy or other energy generated at the facility, or (b) exported from the facility and used elsewhere (e.g., heat used at another facility).

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period.

Cold Storage Transfer
When positive, thermal energy transferred between an HVAC component (such as a chiller) and a thermal storage medium (such as ice) for use in a cooling function at a later time. When negative, thermal energy transferred between the storage medium and an end-use load (such as **Cooling Energy Use**). That is, **Cold Storage Transfer** is positive when the storage medium is being charged (such as making ice) and negative during discharge (such as melting ice to cool a building). (See Section 6.5.4 for further explanation of storage components.)

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period.

Cooling Energy Use
Energy used by air conditioners, chillers, heat pumps (when in the cooling mode[5]), or other devices such as absorption or evaporative coolers that are used to cool buildings. This metric includes compressors, water pumps, condenser fans, cooling tower fans, pneumatic components, and controls. This metric also includes dehumidification, whether it occurs in combination with cooling or in a separate component. Fan energy used to move air through a building, whether or not the air is heated or cooled, is classified as **Air Distribution Energy Use**, and not as heating or cooling energy use. (See also **HVAC Energy Use** in this section.)

Units: kWh, Btu, or Joules

[5] See also Section 6.5.3, Multiple End-Use Equipment.

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

DHW Energy Use

Energy used to heat water for any use other than HVAC or process loads, including any purchased energy and **Facility Energy Production** used for this purpose.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

DHW System Efficiency

Efficiency of the DHW system to deliver hot water to the loads.

DHW System Efficiency = **DHW Load / DHW Energy Use**

Units: Dimensionless

Reported as: Monthly and annual values.

DHW Load

Thermal energy delivered to the DHW distribution system. With reference to Figure 4-2,

$$\text{DHWLoad} = \int \dot{V} \cdot \rho \cdot c_p (T_{HW} - T_{CW})dt \qquad \text{(See note below)}$$

where:

$\dot{V}$ = Volumetric flow rate of cold water entering the domestic water heating system, including cold water entering the mixing valve if present, excluding cold water distributed to the cold water outlets (gal/min or liters/min)

T_{CW} = Cold water temperature measured where $\dot{V}$ is measured (see above) (°F or °C)

T_{HW} = Temperature of heated water entering the hot-water distribution system, measured at the outlet of the mixing valve if present, or at the outlet of the water heater if no mixing valve is present (°F or °C)

ρ = Density of water,[6] 8.3241 lb_m/gal or 0.99757 kg/L

c_p = Specific heat of water,[7] 0.99875 Btu/lb_m·°F or 4.1813 kJ/kg·°C

dt = Differential time increment (min)

Note: In a DAS with a data logger, the formula given above for **DHW Load** may be adapted as follows:

$$\text{DHWLoad} = \rho \cdot c_p \cdot \Delta t \cdot \sum \overline{\dot{V}(T_{HW} - T_{CW})}$$

where:

[6] The given values of ρ and c_p apply for cold water within the range 40°F to 90°F and hot water within the range 110°F to 135°F, with a combined accuracy of ±0.4%. If greater accuracy is needed, or if water temperatures significantly outside of these ranges are expected, the accuracy may be improved by using temperature-dependent properties of water in the data analysis.

[7] See previous footnote.

Δt = Data recording time interval (min)

$\overline{\dot{V}(T_{HW} - T_{CW})}$ = Average value of the product of the flow rate and the temperature difference over the recording interval. This is not the same as the average flow rate times the average temperature difference, which would be inaptly affected by temperatures when the flow rate is zero (Btu/min or kJ/min).

Units: Btu or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total.

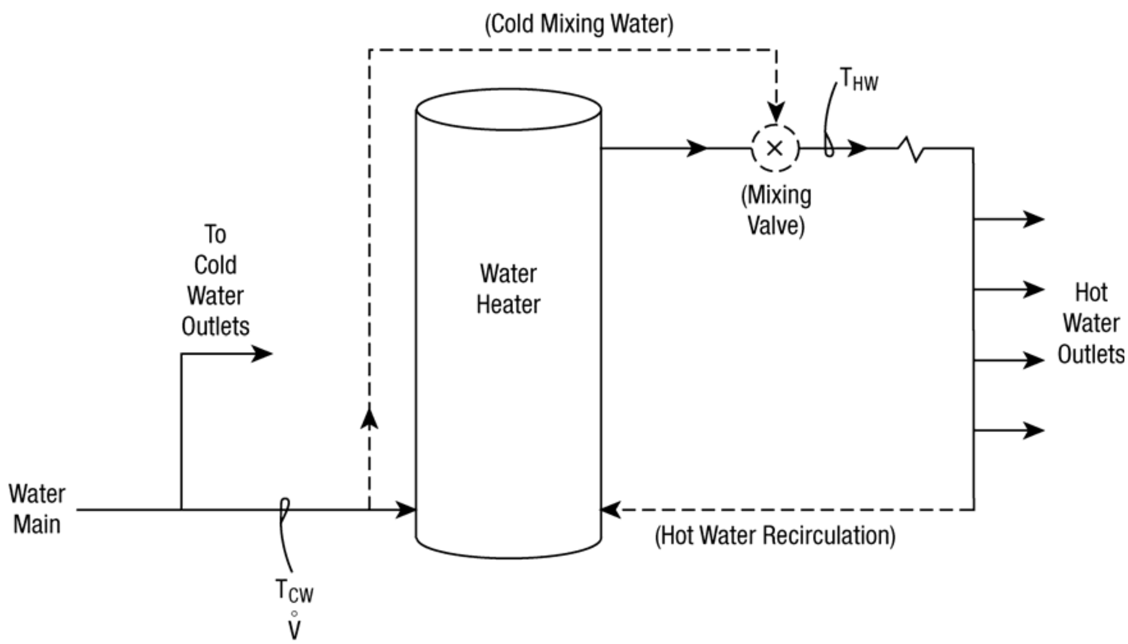


Figure 4-2 ***DHW Load*** **measurement scheme.**
(Features shown with dotted lines may or may not be present in the system.)

Electrical Generation System Losses

Losses in all electrical components that are integral with the facility electrical generating system, but not with one of the generator components. Such components would include an inverter, a transformer (where required as an interface between an inverter and the power grid, for example), or any other nongenerating component of the facility electrical power generation system. This category encompasses components that might serve multiple sources of electricity under the category of **Facility Energy Production.**

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Facade Lighting Energy Use

Energy used to illuminate the exterior surfaces of a building. (All other exterior lighting applications, such as parking lot lights, walkway lighting, and detached sign lighting, are included in **Outdoor Energy Use**.)

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Facility Energy Production

Total of all energy produced at the facility and either used at the facility or sold for use elsewhere, excluding losses within the energy production systems. Includes **Thermal Energy Production** and electrical energy produced by PV, wind, geothermal, or other means, minus **Electrical Generation System Losses**. This metric does not include energy Cogeneration energy output. This metric can be negative if the energy producing systems consume more energy than they generate. In this case, the **Net Facility Energy Use** will be greater than the **Total Facility Energy Use**.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total (Tier 1 or 2); graph of peak day in each billing period (Tier 2 only; see example in Section 7).

Functional Area

An area at a facility, either within a building or outdoors, where energy is used in conjunction with one or more commercial activities.[8] For use in determining the **BEUI**, the **Functional Area** is measured as the **Gross Interior Floor Area** of all spaces that have energy use included in the **Building Energy Use** metric. This may include the whole building, or it may be divided into separate areas with different functions such as office, mercantile, lodging, and parking. For example, in an office building with a parking garage, the **Building Energy Use** and **Functional Area** may be calculated separately for "office" and "parking" **BEUI** metrics, or they may be calculated jointly for an "office/parking" **BEUI** metric.

Units: ft^2 or m^2

Reported as: One or more fixed values

Gross Interior Floor Area

Total interior floor area of a building's spaces, measured from the inside surface of the exterior walls or from the interior surface of walls in common with adjoining buildings. The area of interior columns and pillars is included in this measurement. This metric is measured on a floor-by-floor basis and consists of all *enclosed spaces*, including the area of interior walls, basements, mezzanines, penthouses, equipment rooms, vertical penetrations on each floor (such as elevator shafts, and stairwells), and interior parking. It does not include open covered walkways, courtyards with no roof, balconies, and canopies (Deru and Torcellini 2005b).

Units: ft^2 or m^2

Reported as: One or more fixed values.

[8] Commercial activities are listed in Table 6-2, item I.H.

Heating Energy Use

Energy used by furnaces, boilers, heat pumps (when in the heating mode[9]), electrical resistance coils, or other devices used to heat a building. This metric includes reheat energy, as well as peripheral equipment such as hydronic circulation pumps, boiler feed water pumps, pneumatic components, and controls. Heat pump energy includes compressors, water pumps (for ground-source heat pumps), and evaporator fans (for air-source heat pumps). Fan energy used to move air through a building, whether or not the air is heated or cooled, is classified as **Air Distribution Energy Use**, and not as heating or cooling energy use. (See also **HVAC Energy Use** in this section.)

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

HVAC Energy Use

Heaters, chillers, pumps, fans, pneumatics, controls, and any other loads that constitute the HVAC system.

HVAC Energy Use = Heating Energy Use + Cooling Energy Use + Air Distribution Energy Use + Cold Storage Transfer + Other HVAC Energy Use

(Note: See provisions in Section 6.5.2 for plug-in HVAC loads.)

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Indoor Zone Temperature

Air temperature within each zone of a building that corresponds to the measurement of **Building Energy Use**. The primary purpose of this metric is to qualify comparisons of energy use measurements among buildings, based on the similarity of operating conditions. In a Tier 1 analysis, this may be determined by thermostat set points or building automation system (BAS) control settings. In a Tier 2 analysis, the zone temperatures should be measured directly.

Units: °F or °C

Reported as: Monthly averages, annual average, and graphs that illustrate any significant changes.

Installed Lighting Energy Use

Electrical energy measured in all circuits that are dedicated to indoor lighting fixtures, including energy consumed by lamps, ballasts, control devices, and transformers, adjusted for any nonlighting appliances on these circuits.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

[9] See also Section 6.5.3, Multiple End-Use Equipment.

Net Facility Electrical Demand

Peak electrical demand on the electric utility during the month, as defined in the applicable electric utility rate structure.

Units: kW or kVA, corresponding to the electric utility rate structure

Reported as: Monthly values, annual maximum of monthly values (summer and winter seasonal values can also be reported) including date and time of peak demand values

Net Facility Energy Use

= Total Facility Energy Use – Facility Energy Production

Units: kWh, Btu, or Joules

Reported as: Total and itemized by fuel type. Monthly totals (tabular), monthly daily averages (graphical), annual total (Tier 1 or 2); graph of peak day in each billing period (Tier 2 only; see example in Section 7).

Net Facility Load Factor

A load factor is the average electrical demand divided by the peak electrical demand. The **Net Facility Load Factor** is the load factor as seen by the electrical utility. This metric includes energy exported from the site and can be come negative. A negative load factor has a different meaning and should be interpreted carefully.

Total Facility Load Factor = Hourly average (Electrical **Net Facility Energy Use) ÷ Net Facility Electrical Demand**

Units: Dimensionless

Reported as: Monthly and annual values (summer and winter seasonal values can also be reported)

Net Facility Purchased Energy Cost

Monetary cost of all energy purchased for use at the facility, minus any credits or receipts for energy produced at the facility and sold for use elsewhere.

Units: $\text{Currency}_{\text{Year}}$ (see Section 7.3 for explanation)

Reported as: Monthly and annual values, itemized by fuel type, with electricity cost itemized as usage and demand charges. (All applicable rate structures should be attached as appendices to the report on this procedure (see Section 7).

Other Building Energy Use

Indoor energy consumption that is not included in another category under **Building Energy Use,** excluding **Process Energy Use** and **Cogeneration Losses**. Also, this metric may include exterior energy uses that are considered part of the building, such as pipe freeze protection or roof snow melting. In all cases, the nature of the energy use(s) should be described where this metric is reported. Also, in any graph where **Other Building Energy Use** amounts to more than 5% of **Building Energy Use**, the nature of the energy use(s) should be named or described within the graph or its caption.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Other Facility Electrical Energy Production

Electrical energy produced at the facility by any means, to be specified, not included in one of the other categories under **Facility Energy Production**. In all cases, the nature of the energy production should be described where this metric is reported. Also, in any graph where **Other Facility Electrical Energy Production** amounts to more than 5% of **Facility Energy Production**, the nature of the energy production should be named or described within the graph or its caption.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Other HVAC Energy Use

Energy used by HVAC equipment that cannot be disaggregated among heating, cooling, and air distribution end uses. This metric may include an air compressor that drives pneumatic devices for multiple end uses, heat pump standby losses when the heat pump is neither heating nor cooling, and other cases. See also Section 6.5.3. In all cases, the nature of the energy use(s) should be described where this metric is reported. Also, in any graph where **Other HVAC Energy Use** amounts to more than 5% of **HVAC Energy Use**, the nature of the energy use(s) should be named or described within the graph or its caption.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Outdoor Ambient Temperature

Ambient air temperature at the facility that corresponds to the energy measurements determined in this procedure. In Tier 1, this metric is determined from monthly data available from utility bills or the nearest weather station. In Tier 2, time series data measured at the site.

Units: °F or °C

Reported as: Monthly and annual averages, heating degree-days (HDD, base 65°F), and cooling degree-days (CDD, base 50°F or 65°F). In Tier 1, CDD data obtained from a weather service are typically based on 65°F. In Tier 2, CDD should be derived from measurements at the facility for a 50°F base temperature, which is usually more indicative of commercial building cooling loads. (See ASHRAE [2005], Chapter 32, Annual Degree-Day Method.)

Outdoor Energy Use

The sum of all energy consumed at the facility away from the building, including parking lot lights, walkway lighting, detached sign lighting, snow melting, or other outdoor energy uses. (Facade lighting is included in **Building Energy Use**, not in **Outdoor Energy Use**.)

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

People-Mover Energy Use

Energy consumed in elevators, escalators, moving sidewalks, and other people-moving devices.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Plug-in Lighting Energy Use

Energy consumed in all indoor lighting fixtures that are not connected to a dedicated lighting circuit, estimated as described in Section 6.5.1. This metric may include task lighting, accent lighting, emergency lighting, or other types of lighting plugged into outlets.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period.

(Note: Graphs are constructed based on best estimates of usage schedules and monthly totals.)

Plug Loads Energy Use

Electrical energy measured in all circuits that are dedicated to plug loads, less energy that is included in another category (such as **Process Energy Use** or **Plug-in Lighting Energy Use**).

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Process Energy Use

Energy consumed in a building or elsewhere at a facility to support a manufacturing, industrial, or commercial process other than conditioning spaces and maintaining comfort and amenities for the occupants.[10] Examples include an electrical welder, machine tools, a pottery kiln, an oven in a pizzeria, and a sun lamp in a tanning salon. In an office environment, typical personal computers *are not* categorized as process loads; nor are servers that support building operations. However, server computers at an Internet service provider company *are* process loads. **Process Energy Use** does not include the effect of this energy use on HVAC loads. Any heat recovered and used at the facility in a way that offsets the consumption of purchased energy or other energy generated at the facility is subtracted from **Process Energy Use** and included in the metric that corresponds to the energy use.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Produced Energy Storage Transfer

Energy produced at the facility and transferred to a storage component (when positive) or transferred from a storage component to an end-use load (when negative). Storage components may include batteries, hot-water storage tanks, hydrogen reservoirs, flywheels, and other energy storage devices. (See Section 6.5.4 for further explanation of storage components.) If more than one energy storage component is used at a facility, **Produced Energy Storage Transfer** should be itemized for each component.

[10] Wording adapted from ASHRAE (2004).

Thermal storage of the cooling effect produced by an HVAC component for a load-shifting strategy is included in the metric **Cold Storage Transfer** and not in the metric **Produced Energy Storage Transfer**.

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period.

PV Energy Production

Electrical energy produced by PV modules, less losses in any components that are integral to the PV system. Losses in other components that might serve multiple sources of electricity—such as an inverter or transformer—are grouped separately (see **Electrical Generation System Losses**).

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Thermal Energy Production

Thermal energy generated at the facility by means such as solar thermal or geothermal, to the extent that the energy is used at the facility in a way that offsets the consumption of purchased energy or other energy generated at the facility. This metric does not include the thermal output of cogeneration equipment (see **Cogeneration Thermal Energy Output**).

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total (graph of peak day in each billing period is optional).

Total Facility Electrical Demand

Peak electrical demand of the facility during the month, as defined in the applicable electric utility rate structure. This metric does not include on-site electricity production (**Facility Energy Production**). This metric is the same as the **Net Facility Electrical Demand** if there is no on-site electricity production.

Units: kW or kVA, corresponding to the electric utility rate structure

Reported as: Monthly values, annual maximum of monthly values (summer and winter seasonal values can also be reported) including date and time of peak demand values

Total Facility Energy Use

Total of all energy consumed at the facility. If fuel is stored at the facility, in a fuel oil or LPG tank for example, the fuel use must be metered as it is dispensed from storage (see Section 6.5.4).

Units: kWh, Btu, or Joules

Reported as: Total and itemized by fuel type. Monthly totals (tabular), monthly daily averages (graphical), annual total (Tier 1 or 2); graph of peak day in each billing period (Tier 2 only; see example in Section 7).

Wind Energy Production

Electrical energy produced by wind turbine generators (WTGs) at the facility, minus losses in any components that are integral to the WTGs. Losses in other components that might serve multiple sources of electricity—such as an inverter or transformer—are grouped separately (see **Electrical Generation System Losses**).

Units: kWh, Btu, or Joules

Reported as: Monthly totals (tabular), monthly daily averages (graphical), annual total, graph of peak day in each billing period (see example in Section 7).

Section 5 – Required Additional Procedures

To complete the steps described in this procedure, an additional procedure is required: *Standard Definitions of Building Geometry for Energy Evaluation Purposes* (Deru and Torcellini 2005b). This procedure describes details for determining the **Gross Interior Floor Area** that applies to some of the metrics described here.

Section 6 – Description of Procedure

6.1 – General

This section describes the recommended step-by-step procedure for planning and completing a building energy analysis that will yield measured values of the metrics defined in Section 4. Table 6-1 gives an overview of this procedure. Explanations of each step are given in the sections indicated in the table. This procedure is specifically designed to address the following issues:

- *Standardization.* The performance metrics defined in Section 4 form a consistent basis for comparing energy performance among buildings.
- *Versatility.* The analysis is customized to the facility boundaries, energy configuration, analysis goals, and analysis budget that apply to the project.
- *Economy of Effort.* The data collection is carefully matched to the goals of the analysis and the study questions to avoid the common pitfalls of too few or too many data.

Table 6-1 Procedure Outline

I. Project Definition (Section 6.2)

A. Identify project goals.
B. List specific performance questions to be answered.
C. Determine boundaries of facility to be analyzed.
D. Select Tier 1 or Tier 2 analysis.
E. Specify desired accuracy of results.
F. Estimate budget for project.
G. Identify period of analysis.
H. Assemble basic building data.
I. Obtain pre-existing performance data.

II. Measurement System Design (Section 6.3)

A. Select performance metrics to be measured.
B. Identify data required for each metric.
C. Specify physical location of each measurement.
D. Specify frequency of each measurement.
E. Specify measurement equipment.
F. Determine practicality of measurements.
G. Estimate cost of DAS equipment and operation.
H. Calculate uncertainty of measurements.
I. Resolve cost and uncertainty with expectations (Steps I.E and I.F).

III. Data Collection and Analysis (Section 6.4)

A. Monitor data for quality control.
B. Assemble data for the period of analysis.
C. Calculate monthly metrics.
D. Calculate annual metrics.

IV. Reporting Results
(See reporting formats in Section 7)

6.2 – Project Definition

The form presented in Table 6-2 serves to guide and document the Project Definition stage of the procedure. A user-fillable version of this form is included in the Form Pack attached to this document by a link on the front cover page. Steps I.A through I.I, as shown in Table 6-1, are identified in Table 6-2. Explanations of these steps follow.

Table 6-2 Project Definition Form

Project Name:

Building Address:

All Facility/Procedure Related Contacts:
(Names, organization, title, contact information)

(I.A) Goals of the Analysis:

(I.B) Questions to Be Answered:

(I.C) Facility Definition and Boundaries:

(I.D) Analysis Tier (Tier 1 or Tier 2):

(I.E) Desired Accuracy of Results:
(±____%, or other criteria)

(I.F) Estimated Budget For Performance Analysis:

(I.G) Dates of:
Site visits:
Monitoring period:

(I.H) Basic Building Data:

Building description:
(Floor plan, gross area, floors, space uses, typical occupancy patterns)

Principal Building Function(s):
Principal building types are classified according to the commercial activities, which are types of business, commerce, or function carried on within each building (based on EIA 2003).
Indicate percent floor area for all that apply:

	Education		Health Care		Office		Religious Worship		Parking
	Food Sales		Lodging		Public Assembly		Other Service		Other
	Food Service		Mercantile		Public Order and Safety		Warehouse and Storage		Vacant

Equipment Specifications:
(For all major energy-using equipment at the facility: number, sizes, models, energy ratings, etc.)

Utility Company(s) and Rate Schedule(s):
(Attach to this form)

All relevant Building Drawings: (e.g., floor plans, elevations, electrical panel layouts, lighting plans, HVAC plans, plumbing plans, outdoor lighting plans)
(Obtain at this time)

(I.I) Pre-Existing Performance Data
(Obtain at this time)

Step I.A: Identify project goals. Summarize the purpose of conducting the performance analysis. Some examples of project goals are to

- Understand how energy is used at the facility
- Compare the energy use in this building to that in other buildings
- Qualify for an energy performance rating
- Win an energy conservation award.

Step I.B: List specific performance questions to be answered. Some examples of study questions are

- How much energy is used for lighting?
- What portion of the energy consumption is generated at the facility?
- What is the building energy use per square foot of floor area?

Step I.C: Determine the boundaries of the facility to be analyzed. Define what is included and what is not included in the analysis. See the definition of facility in Section 3.2. It is most convenient if the facility to be analyzed corresponds to the energy utility metering. However, this may or may not satisfy the project goals and the study questions.

Step I.D: Select Tier 1 or Tier 2 analysis. This procedure is divided into two tiers to differentiate the resolution of the results and the amount of effort typically required to complete the procedure. Tier 1 (the simpler level of analysis) results in monthly and annual purchased energy, electrical demand, facility energy production, and related metrics for the facility as a whole, based on utility meter readings, building drawings, a physical examination (walk-through) of the building, and perhaps additional data. Tier 2 (the more detailed level of analysis) yields time-series results, in addition to monthly and annual results, itemized by type of end use, based on submetering and a DAS. Figure 4-1 illustrates the scope of the Tier 1 and Tier 2 analyses.

Completion of either tier requires that at least 1 year of data be collected while the building is in use. Typically, for a Tier 1 analysis of an existing building, such data have already been recorded on utility bills, so the procedure may be completed in a matter of days (see exception discussed below). For a Tier 1 analysis of a new building, a 1-year waiting period will be necessary to collect the data. For a Tier 2 analysis, the measurement (which will take at least 1 year to complete) is part of the procedure.

The four primary metrics determined in a Tier 1 analysis are:

- **Net Facility Energy Use**
- **Net Facility Electrical Demand**
- **Total Facility Energy Use**
- **Facility Energy Production.**

Of these, **Net Facility Energy Use** and **Net Facility Electrical Demand** will generally be available from utility meter readings. If there is no **Facility Energy Production**, the **Total Facility Energy Use** is the same as the **Net Facility Energy Use**. However, if the **Facility Energy Production** is not zero, measured monthly values of this metric are also necessary.[11] If such data are not already on hand (perhaps metered within the facility power system), this metering must be performed as part of this procedure, and will delay the analysis for 1 year. Also, if fuel is stored at the facility (in a fuel oil or LPG

[11] Alternatively, monthly values of the **Total Facility Energy Use** would enable the analysis.

tank, for example), the fuel must be metered as it is dispensed from storage. All the metrics that are determined in a Tier 1 analysis are listed in Table 6-3, which is discussed in Section 6.3.

Tier 2 metrics are itemized by end use and recorded as time-series data with a DAS for 1 year. From the time-series data, monthly and annual totals are also determined. All the metrics that are determined in a Tier 2 analysis are listed in Table 6-4, which is discussed in Section 6.3.

Step I.E: Specify desired accuracy of results. More precise measurements will require more expensive monitoring equipment. Referring to the project goals (Step I.A) and study questions (Step I.B) should help put this into perspective.

Step I.F: Estimate budget for project. The budget may dictate the level of effort, or the necessary level of effort may dictate the budget, or the trade-off between the two may be considered. In the budget, include:

- The Project Definition effort
- The DAS purchase, installation, and operation (data collection), if used
- The analysis and reporting effort.

Step I.G: Identify period of analysis. For a Tier 1 analysis, the period might correspond to the most recent year of utility bill records. For a Tier 2 analysis, it might be based on the time required to design, install, and commission a DAS, and then to operate it for 1 year. In either case, select a year that is representative of the normal, occupied function of the facility.

Step I.H: Assemble basic building data. Specific information about the building, which should be gathered before the Measurement System Design phase begins, is detailed in Table 6-2.

Step I.I: Obtain pre-existing performance data. Assemble any pre-existing performance data, including utility bills, installed metering, and engineering records.

6.3 – Measurement System Design

The purpose of the measurement system design is to ensure that the data collected will correspond to the desired analysis and results. This should help to eliminate two of the most common problems in building analysis: (1) insufficient data to complete the desired analysis, and (2) extraneous data that are collected but never used.

Checklists are provided here for completing the first five steps of the measurement system design. Blank forms are provided in Tables 6-3 and 6-4, for Tier 1 and Tier 2 analyses, respectively. User-fillable versions of these forms are included in the Form Pack attached to this document by a link on the front cover page. Sample Tier 1 and Tier 2 measurement system designs are shown in Appendix A. Steps II.A through II.E correspond to columns in these forms.

Completing the Measurement Planning Form

Step II.A: Select performance metrics to be measured. Review the list of performance metrics defined in this procedure, which are listed in the "Performance Metric" column, and ascertain which ones apply to the analysis at hand. Cross out any metrics that correspond to features that the facility does not have and any metrics for which results are not desired. If the goals of the analysis (Step I.A) and the study questions (Step I.B) require measurements not defined in this document, include these metrics as additional items in the Performance Metrics column, so that the Measurement System Design will include them. The names of any user-defined metrics should be distinct from those of all the standard metrics defined in Section 4, which are reserved for the use indicated by those definitions.

Step II.B: Identify data required for each metric. For each item remaining in the checklist, note in the "Necessary Data" column the data that are needed to compute the metric. Consult the metric definitions in Section 4 for details. In addition, apply the concerns discussed in Section 6.4 (Energy Balances and Unmeasurable Metrics) at this stage. In some cases, the data may consist of other items in the checklist.

Step II.C: Specify the physical location of each measurement. For each necessary data stream, note in the "Point of Measurement or Source of Data" column the physical location at the facility where these data will be measured or the source of data if not measured on site. The point of measurement may include utility meters, building drawings, specifications, walk-through inspections, and interviews with the building engineer and building occupants, in addition to any new measurement equipment to be installed.

Step II.D: Specify the recording frequency of each measurement. For each required measurement, note in the "Recording Frequency" column the appropriate time interval. As described in Step I.D, a Tier 1 analysis requires monthly data and a Tier 2 analysis requires time-series data (see definition in Section 3.2).

Step II.E: Specify measurement equipment. For each required measurement, list in the "Measurement Equipment" columns the measurement device(s) to be used. See Appendix B for guidance on selecting equipment.

Additional Steps in the Measurement System Design

Step II.F: Determine the practicality of the measurements. After you outline the measurement devices and the locations where they will be installed, it is important to verify that this plan is practical. You may need to modify project goals, the tier level, accuracy requirements, or the list of included performance metrics based on the practicality of the measurements. Three important tasks are to:

- *Verify configurations*. Inspect the building wiring and any other features identified in the "Point of Measurement" column, to verify that the physical configuration matches the drawings or assumptions on which the plan is based and that it enables the planned measurements. Examples of features to check include circuit breaker configuration, access to wiring for measurement purposes, plumbing configuration, and clearances for installing measurement devices.

- *Verify code conformity*. Review the measurement system design with the local building department or any other authority that has jurisdiction, to verify that the planned location of measurement devices will not violate any applicable building codes. If necessary, obtain an exception to the code *before* installing the measurement equipment.

- *Check warranty concerns.* Ensure that the placement of measurement devices in particular pieces of equipment does not void manufacturers' warranties.

Step II.G. Estimate the cost of DAS equipment and operation. If any new measurements are needed, include the following items when estimating the cost of implementing the measurement plan:

- The measurement equipment listed in Step II.E
- A data logger or other means of recording all the required measurements
- Installation and commissioning of the above equipment
- The data collection effort: In addition to designing and installing DAS hardware that can collect the required data, technical staff must be furnished to operate the DAS. Experience has shown that hardware failures do occur, and these can result in significant data loss if any problems that arise are not promptly detected and remedied. At this stage, the following questions must be answered:

    - Who will be responsible for data collection and quality control?
    - How many hours per week will the responsible party(s) spend on this task?
    - How will the data be collected and reviewed?
      (A telephone modem or network connection is recommended for remote monitoring.)
    - How often will the data be checked?
      (Daily review is recommended initially, during commissioning. Weekly review is the suggested minimum frequency for the duration of the data collection period. Software that checks the data continuously and sends fault alarms to the technical staff is recommended.)

Step II.H. Calculate uncertainty of measurements. For each metric, calculate the measurement uncertainty as described in Appendix C.

Step II.I. Resolve cost and uncertainty with expectations. Before purchasing DAS equipment, compare the estimated cost (Step II.G) and measurement uncertainty (Step II.H) to the expectations that were set in the Project Definition phase (Steps I.E and I.F). To resolve any disparity, modify the estimated budget, the expected accuracy, or the design of the measurement system.

Table 6-3 Tier 1 Measurement Planning Form

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
1	**Gross Interior Floor Area**			One Time	N/A	N/A
2	**Functional Area**			One Time	N/A	N/A
3	**Total Facility Energy Use**			Monthly		
4	**Facility Energy Production**			Monthly		
5	**Net Facility Energy Use**			Monthly		
6	**Net Facility Electrical Demand** [1]			Monthly		
7	**Net Facility Purchased Energy Cost**			Monthly		
8	**Net Facility Load Factor**			Monthly		
9	**Indoor Zone Temperature**			Monthly		
10	**Outdoor Ambient Temperature** (also HDD and CDD)			Monthly		
	(User-defined metric)					
	(Etc.)					

[1] If there is no on-site electricity generation or electricity from co-generation equipment, the **Net Facility Electrical Demand** becomes the **Total Facility Electrical Demand**.

Table 6-4 Tier 2 Measurement Planning Form

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
1	**Gross Interior Floor Area**			One time	N/A	N/A
2	**Functional Area**			One time	N/A	N/A
3	**Installed Lighting Energy Use**			Time series		
4	**Plug-In Lighting Energy Use**			(See Section 6.5.1)		
5	**Facade Lighting Energy Use**			Time series		
6	**Building Lighting Energy Use**			Time series		
7	**Heating Energy Use**			Time series		
8	**Cooling Energy Use**			Time series		
9	**Air Distribution Energy Use**			Time series		
10	**Cold Storage Transfer**			Time series		
11	**Other HVAC Energy Use**			Time series		
12	**HVAC Energy Use**			Time series		
13	**DHW Energy Use**			Time series		
14	**DHW Load**			Time series		
15	**DHW System Efficiency**	Use items 13, 14	N/A	Monthly	N/A	N/A
16	**Plug Loads Energy Use**			Time series		
17	**People-Mover Energy Use**			Time series		
18	**Other Building Energy Use**			Time series		
19	**Building Energy Use**			Time series		

Table 6-4 Tier 2 Measurement Planning Form (continued)

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
20	**Building Energy Use Intensity**	Use items 2, 19	N/A	Annual	N/A	N/A
21	**Building Purchased Energy Cost**		Utility Bills	Monthly	N/A	N/A
22	**Building Purchased Energy Cost Intensity**	Use items 2, 21	N/A	Annual	N/A	N/A
23	**Building Electrical Demand**	Use item 19	N/A	Monthly	N/A	N/A
24	**Building Electrical Demand Intensity**	Use items 2, 23	N/A	Monthly	N/A	N/A
25	**Process Energy Use**			Time series		
26	**Outdoor Energy Use**			Time series		
27	**Cogeneration Fuel Use**			Time series		
28	**Cogeneration Electrical Energy Output**			Time series		
29	**Cogeneration Thermal Energy Output**			Time series		
30	**Cogeneration Losses**	Use items 27, 28, 29	N/A	Time series	N/A	N/A
31	**PV Energy Production**			Time series		
32	**Wind Energy Production**			Time series		
33	**Other Facility Electrical Energy Production**			Time series		
34	**Electrical Generation System Losses**			Time series		
35	**Thermal Energy Production**			Time series		
36	**Produced Energy Storage Transfer**			Time series		
37	**Facility Energy Production**			Time series		
38	**Total Facility Energy Use**			Time series		

Table 6-4 Tier 2 Measurement Planning Form (continued)

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
39	**Net Facility Energy Use**			Time series		
40	**Net Facility Purchased Energy Cost**		Utility Bills	Monthly	N/A	N/A
41	**Total Facility Electrical Demand**	Use item 38	N/A	Monthly	N/A	N/A
42	**Net Facility Electrical Demand**	Use item 39	N/A	Monthly	N/A	N/A
43	**Net Facility Load Factor**	Use items 39, 42	N/A	Monthly	N/A	N/A
44	**Indoor Zone Temperature**			Time series		
45	**Outdoor Ambient Temperature** (also HDD and CDD)			Time series		
	(User-Defined Metrics)					

6.4 – Data Collection and Analysis

The task of data collection, if needed, consists of purchasing, installing, commissioning, and operating the DAS specified in the Measurement System Design phase, and monitoring the data for quality control. The quality control guidelines are described in Step II.G. Some analysis (for example, determining the monthly values of all the applicable metrics) should be conducted concurrently with data collection, to verify that the data set is complete and yields credible results.

The data analysis task consists of determining values of all applicable metrics based on the collected data. Some recommended practices follow.

- *Energy Balances.* In cases where one metric is the sum of (or difference between) several other metrics, the recommended practice is to measure each metric individually and use the summation as a check on the consistency of the data. This practice is also a more accurate way to determine a total, rather than summing the constituent metrics. Any inconsistencies should be reconciled (corrected, or at least understood and reported).
- *Unmeasurable Metrics.* If a metric cannot practically be measured directly, it may need to be determined based on a sum of or difference between other metrics. However, this practice sacrifices the benefit of energy balance checking, and is less accurate.
- *Missing Data.* If intervals of data are missing because of a DAS malfunction, one of the following approaches should be applied:

- Extend the period of data collection, so that a complete year of data is obtained, and modify the period of analysis to use the complete year of data.

- Apply the best available method for estimating the missing data, and include the uncertainty introduced by this method in the reported measurement uncertainty. (Large, continuous gaps are more difficult than intermittent lapses to restore.)

- Report "Missing Data" in lieu of metrics for the periods affected.

In any case, maintain a log of all missing data and the method(s) used to reconcile the missing data.

6.4.1 – Monthly Analysis

The following procedures should be used to account for months that may vary in length, and for various utility billing periods.

Identify Analysis Months

Standard months are January through December, corresponding to the Gregorian calendar. Nonstandard months may be any 12 approximately equal divisions of a year. For example, nonstandard months may correspond to a utility billing cycle, provided it consists of 12 consecutive, approximately equal intervals that cover approximately 365 days. They may be named January, February, and so on, according to the standard month in which most of the days occur. Alternatively, they may be named Month 1, Month 2, etc., or another convenient designation.

For a Tier 1 analysis, in which the primary source of energy use data is utility bills, the analysis months should be chosen to correspond to the utility billing cycle. If more than one utility is used, and they are on different billing cycles, the one with the highest annual use should be favored. This approach minimizes errors caused by estimating the portion of the utility use that occurs within the analysis month (see *Accommodate Nonsynchronous Utility Billing Periods,* below).

Use Average Daily Values

Monthly metrics should be reported as monthly totals in tabular form (Table A-4) and as average daily values in graphical form (Figure A-3). The use of average daily values prevents the weighting of metrics by the number of days per month, which may vary slightly from one month to another.

Identify the Analysis Year

Annual totals are determined by summing 12 consecutive monthly totals and adjusting for the number of included days. An analysis year consists of 365 consecutive days, whether or not the data were collected during a leap year.[12] In the event that the 12 consecutive months amount to slightly more or fewer than 365 days, the total should be adjusted by adding or subtracting average daily values symmetrically at the beginning and end of the analysis year.

<u>Examples</u>:

1. <u>Standard months in a leap year</u>.
   A sum of energy totals for January through December includes 366 days. This sum is adjusted to 365 days by subtracting one half of the average daily value for January and one half of the average daily value for December.

[12] This is to avoid a slight bias in annual metrics measured in leap years versus nonleap years.

2. Utility billing periods that cover fewer than 365 days.
   The utility bill analysis year runs from April 3 through March 29. The variations in the meter reading dates cause these 12 consecutive months cover only 361 days. Thus, the annual total is adjusted to 365 days by adding 2 times the average daily value for "April" and 2 times the average daily value for "March."

Accommodate Nonsynchronous Utility Billing Periods

If one or more utilities (e.g., electricity and natural gas) are billed on schedule(s) that do not correspond to the analysis months, the following procedure should be used to determine monthly metrics that involve the utilities in a Tier 1 analysis.

For each day in the analysis month, for each utility, the average daily value of the utility use for the billing period that includes the day in question applies. These values are totaled for each utility, for each day in the analysis month, to determine the monthly total. Finally, the monthly totals are divided by the numbers of days in the analysis months to determine the average daily values.

Example:

Standard months are used for January 1 to December 31, 2005 (not a leap year). Electricity is billed on the 10th of each month. Natural gas is billed on the 20th of each month.

- For January 1, 2005 through January 10, 2005, the daily electricity use is the average daily value for the billing period December 10, 2004 to January 10, 2005. The gas use is the average daily value for the billing period December 20, 2004 to January 20, 2005.

- For January 11, 2005 through January 20, 2005, the daily electricity use is the average daily value for the billing period January 10, 2005 to February 10, 2005. The gas use is the average daily value for the billing period December 20, 2004 to January 20, 2005.

- For January 21, 2005 through January 31, 2005, the daily electricity use is the average daily value for the billing period January 10, 2005 to February 10, 2005. The gas use is the average daily value for the billing period January 20, 2005 to February 20, 2005.

The January totals are determined by summing the daily values from January 1, 2005 through January 31, 2005. Then the average daily values are determined by dividing the January totals by 31 days.

6.5 – Special Instructions

6.5.1 – Plug-in Lighting Energy Use

When plug-in lighting fixtures such as task lighting or accent lighting are combined on the same circuits with other plug loads, a method should be used to either measure or estimate this metric as accurately as is practical. The following two methods are recommended:

- *Instrumented Audit (preferred method)*
  - If there are few plug-in lighting fixtures, using individual meters to measure the energy use of each fixture may be practical. For example, plug-in meters are available that tally watt-hours of

energy used by one or two plug loads. Such instruments may be read monthly, either by visual inspection or modem connection, to indicate monthly values of the energy use for each fixture.

- If many identical plug-in lighting fixtures are used in a consistent manner (similar use schedules), monitoring a sample of them in the manner described earlier, and then scaling the results to estimate the energy use of all the fixtures, may be practical.

- In either case, the period of measurement must be a good representation of the period of analysis. For example, seasonal variations and vacation schedules must be taken into account. The recommended procedure is to continue the measurements for 1 year, unless a shorter period of measurement is obviously a good representation of the entire year.

• *Uninstrumented Audit (alternate method)*
  When an instrumented audit is not practical, the following procedure is an alternate approach.

  - Determine the amount of plug-in lighting present in a zone by a walk-through inspection. During the walk through, count the number of each type of fixture and note the power consumption of each type.

  - Determine the use schedule of the plug-in lighting by visually inspecting the zone during a period of occupancy. In addition, conduct an oral or written survey of either (a) one person who has knowledge of the use schedules in the zone, or (b) a sample of the zone occupants who use the plug-in lighting. In the survey, address seasonal variations, vacation schedules, and any other variations.

  - Estimate the **Plug-in Lighting Energy Use** based on the amount of installed wattage and the use schedules.

  For dissimilar zones, conduct this type of audit for each type of zone. For numerous zones of the same type, conduct an audit for one zone and apply it to similar zones.

6.5.2 – Plug-in HVAC Appliances

For plug-in HVAC appliances, such as portable heaters or window-mounted air conditioners, the best practical effort should be made to measure or estimate these loads. The Instrumented Audit procedure described in Section 6.5.1 should be used whenever practical, in order to capture the effects of irregular usage schedules as well as cycling on and off caused by thermostatic controls. Deduct the energy used for plug-in HVAC appliances from the **Plug Loads Energy Use** and include it in both **HVAC Energy Use** and the appropriate submetric (**Heating Energy Use** or **Cooling Energy Use**).

6.5.3 – Multiple End-Use Equipment

If one appliance serves multiple end uses, the energy use should be disaggregated by end use whenever practical, according the scheme of metrics diagrammed in Figure 4-1 and defined in Section 4. If disaggregating the end uses is not practical, report this energy use as an aggregate.

For example, if a heat pump is used both for heating and cooling, the DAS should include a measurement that indicates the mode of operation, such as:

• A control signal
• An energy management system log

- Measurement of the supply and return air temperature differential. (This method is less decisive and less preferred.)

The energy consumed by the heat pump should be allocated to **Heating Energy Use** or **Cooling Energy Use** according to the mode of operation in each time step. However, if this heat pump also features a conditioned air distribution fan that is on the same electrical circuit and serves more than one zone, disaggregating the **Air Distribution Energy Use** from the **Heating Energy Use** and **Cooling Energy Use** might not be practical. In this case, the energy use should be reported as **Other HVAC Energy Use**, along with an explanation of the special circumstances.

Energy used by a controller that is integral to a furnace should be reported as **Heating Energy Use**. Energy used by a controller that is integral to a heat pump, which both heats and cools a building, should be included in **Heating Energy Use** when the heat pump is running in the heating mode, and as **Cooling Energy Use** when in the cooling mode. However, when the heat pump is in the standby mode (neither heating nor cooling), the standby energy use should be reported as **Other HVAC Energy Use**.

6.5.4 – Storage Components

Any component that stores energy[13] or fuel from one time interval to the next is referred to in this procedure as a storage component. In a Tier 1 analysis, the time intervals of interest are months. In a Tier 2 analysis, time series (see definition in Section 3.2) data are involved. In either case, the energy performance analysis must account for any transfer of energy into or out of storage. Storage components may include, but are not limited to:

- Tank for on-site storage of purchased fuel (e.g., heating oil or LPG)
- Battery
- Hot-water storage tank
- Cold storage (e.g., ice)
- Hydrogen reservoir (pressure tank or other mechanism)
- Flywheel.

Figure 6-1 shows a schematic diagram of a generic storage component. The four primary variables that are significant at the system level are:

- Input: Energy transferred to the storage component (kWh, Btu, or Joules)
- Output: Energy transferred from the storage component to a load (kWh, Btu, or Joules)
- Losses: Energy dissipated with no useful application (kWh, Btu, or Joules)
- State-of-charge (SOC): Amount of energy available for transfer or loss (kWh, Btu, or Joules)

In any time interval, these four variables are interrelated as follows:

$$\text{Input} - \text{Output} - \text{Losses} - \Delta\text{SOC} = 0$$

where:

$$\Delta\text{SOC} = \text{Final SOC} - \text{Initial SOC}$$

[13] This does not include natural energy flows, such as thermal energy stored in the building mass by natural convection and radiation. See also Section 2.3.

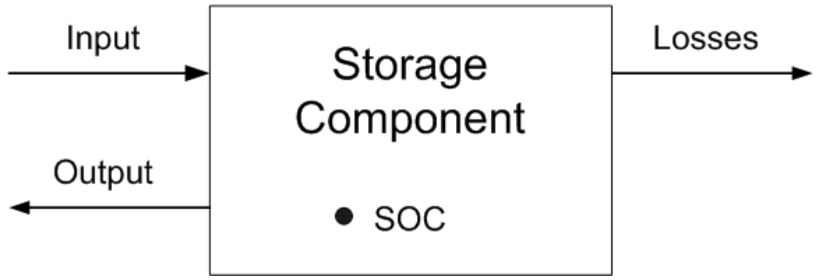


Figure 6-1 Generic storage component

Thus, if any three of the primary variables are measured, the fourth may be calculated. Losses are generally difficult to measure. SOC is sometimes easy to measure; however, SOC of electrical batteries and LPG tanks is more difficult. For a Tier 1 or Tier 2 analysis with this procedure, it is only necessary to determine input and output, because this is adequate for the purpose of tracking energy consumption by end use.

In this procedure, purchased fuel storage is handled differently than the storage of energy or fuel that is produced at the facility.

Purchased Fuel Storage

If purchased fuel (such as heating oil, coal, or LPG) is stored on site, the fuel enters the energy performance analysis only when it is consumed. Thus, any "Fuel Use" or "Energy Use" metric that involves the use of fuel that has been stored, refers to the output from the storage component. Two methods for measuring the output from a fuel storage component are:

1. Measure the amount of fuel dispensed.

2. Verify that losses are negligible; log all fuel purchases (input); measure the SOC at the beginning and end of each time interval (as with a dip stick in a fuel tank); and calculate the output with the equation:

   Output = Input – ΔSOC

Produced Energy Storage

If energy, including electrical, thermal, chemical (such as hydrogen), and mechanical (such as a flywheel), is produced on-site, both the input and the output enter the energy performance analysis. In the interest of keeping the metric definitions as concise as possible, we define:

Storage Transfer = Input – Output

Thus, storage transfer is positive during the charge and negative during the discharge of a storage component. This definition applies to the following Tier 2 metrics (see Section 4.1 for definitions):

- **Produced Energy Storage Transfer**
- **Cold Storage Transfer**

If more than one type of energy storage component is used for energy that is produced at the facility (such as batteries and a solar hot-water storage tank), **Produced Energy Storage Transfer** should be itemized for each component. Any further analysis of storage components, such as determining losses and SOC, is at the user's discretion and is not included in a Tier 2 analysis.

6.5.5 – Pump and Fan Energy

In general, energy consumed by a pump or a fan is included in the metric for the associated end use. Pumps are usually associated with space heating, space cooling, or DHW. Table 6-5 lists some examples of pump applications with the associated metrics. If the pumps or fans serve multiple HVAC systems that are heat and cooling simultaneously, then all of the energy is be classified as **HVAC Energy Use**.

The situation with fans is similar. However, the function of ventilation (the intentional introduction of outside air into a building) is usually combined with air distribution for space heating or cooling. For example, air moved by an air handler to various zones within a building may be heated, cooled, neither, or both at the same time (for different zones); and it may consist of 100% return air, 100% outside air, or a mixture of outside air and return air that may vary over time. Thus, it is often impractical to disaggregate energy used for air movement according to the end uses of heating, cooling, and ventilation. For this reason, the metric **Air Distribution Energy Use** encompasses all these applications (see also definition of this metric in Section 4.1). Table 6-6 lists some examples of fan applications with the associated metrics.

Table 6-5 Metrics for Pump Applications

Application	Metric
Hydronic heat distribution	**Heating Energy Use**
Boiler feed water	**Heating Energy Use**
Ground water circulation loop for a ground source heat pump (HP)	**Heating** or **Cooling Energy Use** (depending on mode of HP)
Run around loop for a water based heat recovery system	**Heating** or **Cooling Energy Use** (depending on mode)
Chilled water distribution	**Cooling Energy Use**
Cooling tower for chiller	**Cooling Energy Use**
Evaporative cooler wick circulation	**Cooling Energy Use**
DHW recirculation loop	**DHW Energy Use**

Table 6-6 Metrics for Fan Applications

Application	Metric
Air Handler	**Air Distribution Energy Use**
Supply or Exhaust Ventilation	**Air Distribution Energy Use**
Heat or Energy Recovery Unit	**Air Distribution Energy Use**
Outdoor Air Conditioner Coil Fan	**Cooling Energy Use**
Outdoor Heat Pump Coil Fan	**Heating Energy Use**
Cooling Tower for Chiller	**Cooling Energy Use**
Indoor Fan-Coil Unit (Single-Zone)	**Heating Energy Use** or **Cooling Energy Use**

Section 7 – Reporting Format

This section provides a set of standard formats for reporting on building energy performance in a consistent manner. The reporting format consists of the following items:

7.1 – Tier 1

- Project Definition form (Table 6-2)
- Diagram of measurement scheme that shows locations of measurements, similar to the example in Figure 7-1
- Table of Monthly Metrics, including all metrics listed in the Measurement Plan, which uses the format illustrated in Table 7-1 (A user-fillable version of this form is included in the Form Pack attached to this document by a link on the front cover page.)
- Graph that shows monthly metrics and uses daily average values, similar to the example in Figure 7-2.

7.2 – Tier 2

- Project Definition form (Table 6-2)
- Diagram of measurement scheme that shows locations of measurements, similar to the example in Figure 7-1
- Table of Monthly Metrics, including all metrics listed in the Measurement Plan, which uses the format illustrated in Table 7-1 (A user-fillable version of this form is included in the Form Pack attached to this document by a link on the front cover page.)
- Graph that shows monthly metrics and uses daily average values, similar to the example in Figure 7-2
- Monthly graphs of peak-day profiles by end use that use the format illustrated in Figure 7-3.

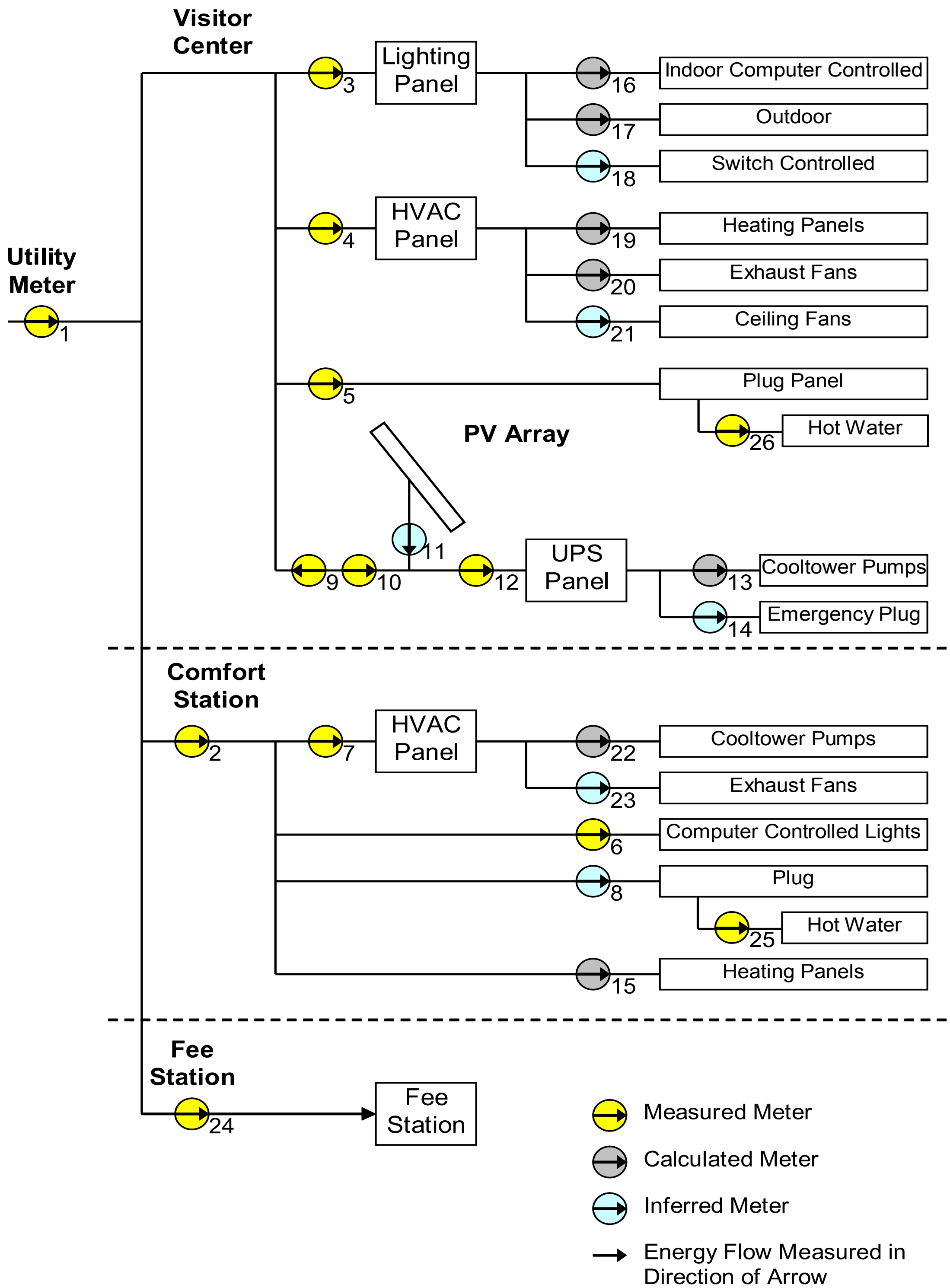


Figure 7-1 Example diagram of a measurement scheme

Table 7-1 Monthly and Annual Metrics

(Tier 1 metrics shown.)

Metric	Units	Month												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	
Total Facility Energy Use														
Net Facility Purchased Energy Cost														
Facility Energy Production														
Net Facility Energy Use														
Net Facility Electrical Demand														
Indoor Zone Temperature														
Outdoor Ambient Temperature														
Heating Degree Days (base 65°F)														
Cooling Degree Days (base ___°F)														

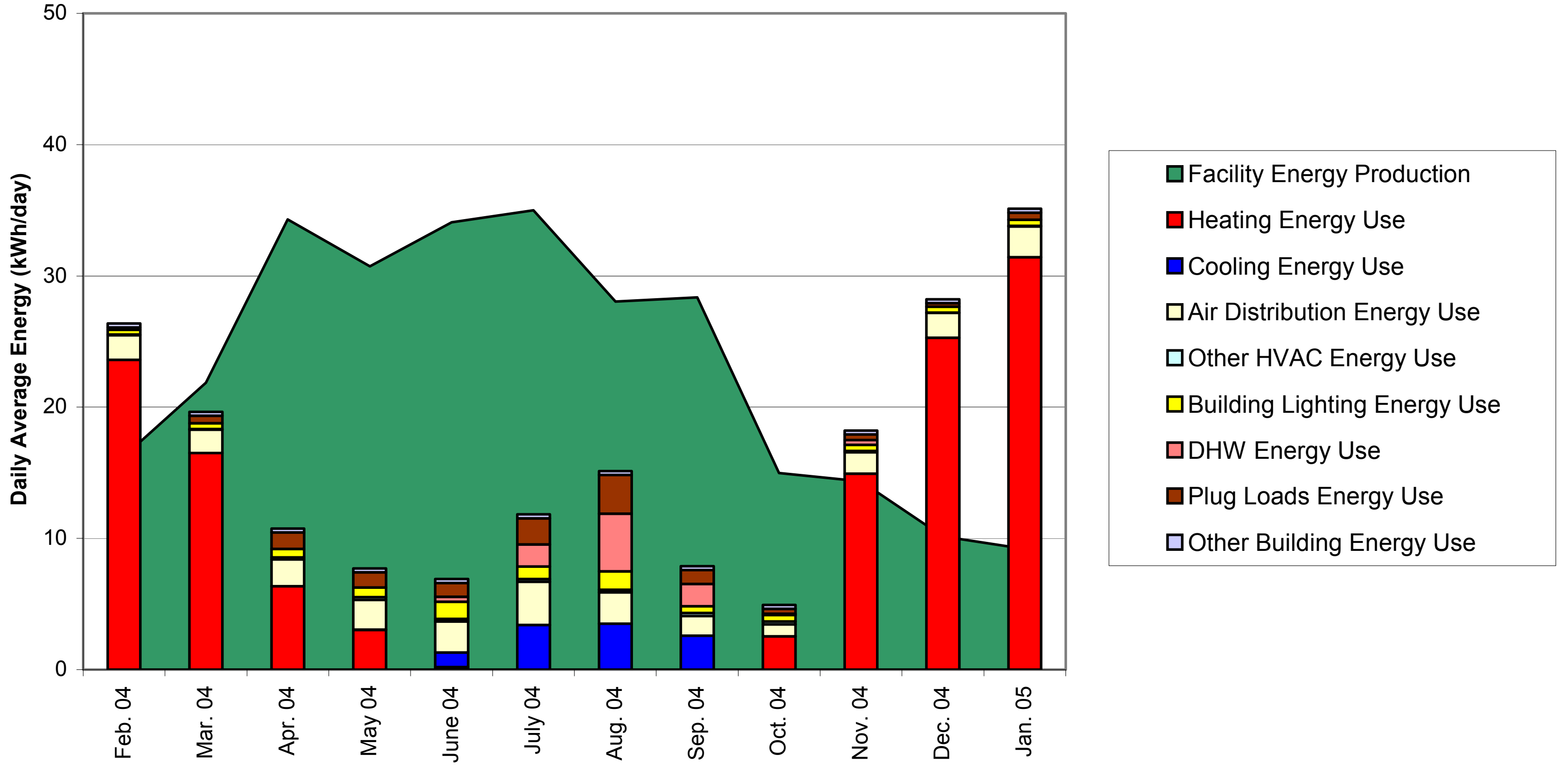


Figure 7-2 Example graph showing monthly metrics as daily averages

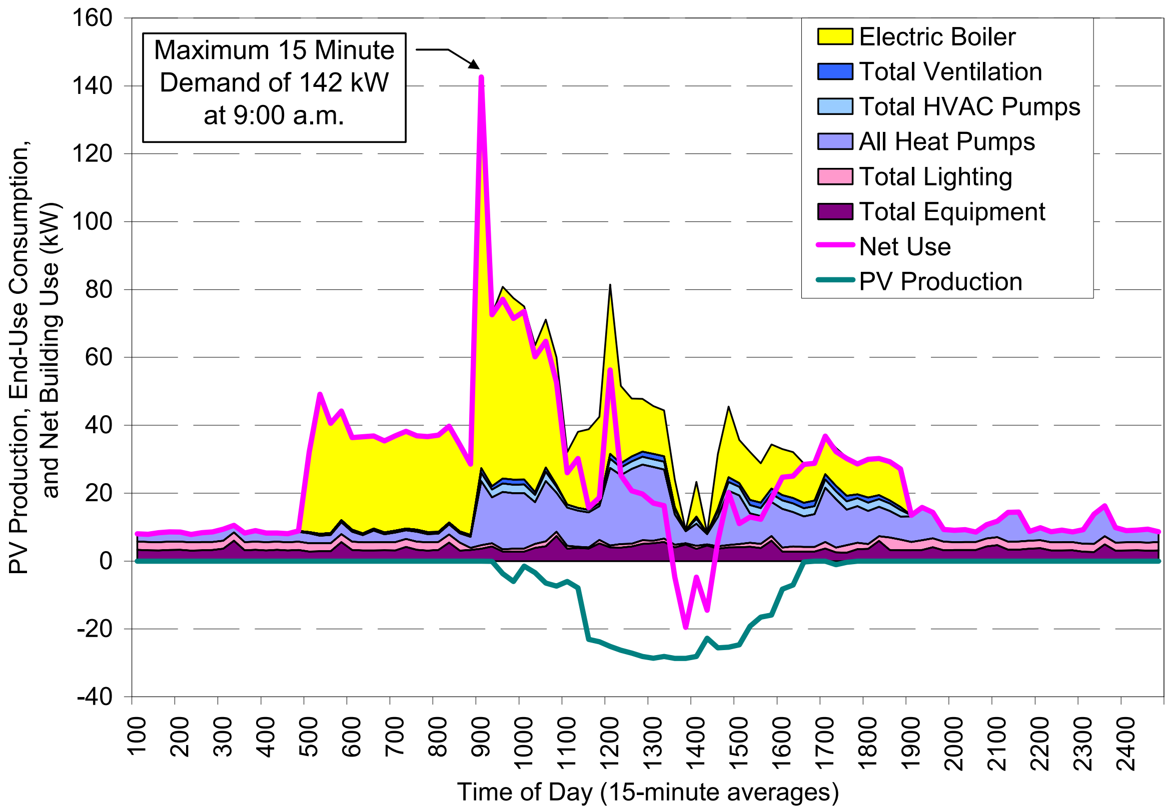


Figure 7-3 Example graph of peak-day profiles

7.3 – Reporting Cost Metrics

When energy costs are compared between two buildings that have been analyzed at different times or in different places, several factors may bias the comparison:

- Changes in energy prices over time
- Differences in energy prices from place to place
- General inflation that occurs during the time interval
- Exchange rates between different currency units, which vary over time.

It is beyond the scope of this procedure to develop a system for normalizing all these effects. However, the following procedures should be used to report cost metrics in a way that will facilitate their interpretation.

The following metrics defined in this procedure include units of currency:

- **Net Facility Purchased Energy Cost**, $\text{Currency}_{\text{Year}}$
- **Building Purchased Energy Cost**, $\text{Currency}_{\text{Year}}$
- **Building Purchased Energy Cost Intensity**, $\text{Currency}_{\text{Year}}/\text{ft}^2$ or $\text{Currency}_{\text{Year}}/\text{m}^2$

In each case where currency units are used, the year during which the expenditures occurred should be noted. If the analysis year extends over two calendar years, the calendar year during which most of the expenditures occurred should be cited.

Examples:

- **Net Facility Purchased Energy Cost** (Annual) = US$$_{2001}$6,500/yr
- **Building Purchased Energy Cost Intensity** (Annual) = US$$_{2003}$0.87/ft^2·yr

In addition, footnotes should be used to reference the building location and the applicable utility rate schedule(s). These are documented in the Project Definition Form (Table 6-2).

Section 8 – References

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Appendix A – Sample Project

A.1 – Introduction

This sample project is provided as an example of the procedure presented in Section 6. For illustrative purposes, both Tier 1 and Tier 2 analyses are outlined in the Measurement System Design phase. However, only the Tier 2 analysis was completed; results are reported here.

The building to be analyzed is the newly constructed Science House at the existing Science Museum of Minnesota in St. Paul. This small (1,370-ft^2), one-story building contains museum exhibits, a lecture or presentation area, a private office, and restrooms, all associated with an outdoor exhibit area around the building called the Big Back Yard. (The outdoor exhibit has no energy use distributed through the Science House building.) Energy features of the Science House include:

- Passive solar heating (large, south-facing windows with low-e glazing, and a dark-colored concrete slab floor).

- An 8.7-kW photovoltaic (PV) system integral with the roof. Four inverters convert the direct current (DC) power generated by the PV modules to alternating current (AC) power for use in the Science House or for export to the main museum building (with possible, but unlikely, sale of excess to the electric utility company).

- A daylighting system with ample south windows, clerestory windows, and an automatic dimming control on the electric lights.

- A ground-coupled heat pump system that heats and cools the building and may also heat domestic hot water (DHW).

- A heat recovery ventilator. It is ducted to draw exhaust air from restrooms. It is controlled by occupancy detectors in the restrooms, as well as a carbon dioxide detector in the presentation area.

The mechanical equipment room is located in an open loft, in view of the museum guests, with a sense that the energy features of the building are part of the exhibit. The only purchased energy is electricity, via an underground feed from the main museum building.

The construction of the Science House building was completed in June 2003. Construction of the outdoor exhibit began in 2003, and the exhibit opened in June 2004. The period of data collection and analysis was February 1, 2004 through January 31, 2005. The Science House was used as a construction job site office until May 2004. It then was unoccupied while the building's interior finishing work was completed, until the outdoor science park, the Big Back Yard, opened on June 24. It then served as public exhibit 7 days a week, from 9:30 a.m. to 8:30 p.m. (Sundays 9:30 a.m. to 5:00 p.m.) until Labor Day. During these times, visitors came and went continually. The daily period of heaviest use was typically from 11:00 a.m. to 3:00 p.m. After Labor Day, the park (and consequently the Science House) was only open on weekends from 9:30 a.m. to 6:00 p.m. After the park closed for the season on October 3, the building was usually unoccupied, the thermostat was turned down to 64°F, the water heater was turned off, and all plug loads were unplugged. For the remainder of the analysis year, the building was used only for occasional museum staff meetings.

A.2 – Project Definition

Table A-1 presents the Project Definition stage of the procedure.

Table A-1. Sample Project Definition

Project Name:

Science Museum of Minnesota – Science House

Building Address:

Science Museum of Minnesota
120 W. Kellogg Blvd.
St. Paul, MN 55102

All Facility/Procedure Related Contacts:
(Names, organization, title, contact information)

Museum director:	(Not included in this document)
Energy consultants:	(Not included in this document)
PV contractor:	(Not included in this document)

(I.A) Goals of the Analysis:

1. Evaluate the energy performance (energy use, energy production, and net energy use) of the building as a whole.
2. Evaluate how energy is used in the building (breakdown by end uses).
3. Support an exhibit that features a real-time display of the building's energy performance.

(I.B) Questions to Be Answered:

1. What is the total energy use of the Science House?
2. What is the total energy production of the PV system?
3. What is the net energy use of the facility?
4. What is the energy consumption for each end use?
5. What temperature and humidity ranges are maintained in the building?

(I.C) Facility Definition and Boundaries:

The facility consists of the Science House building, a nearby shed that is electrically connected to the Science House, and any outdoor loads distributed through the Science House. Although this building is not metered separately by the electric utility company, this is the extent of the new construction and the scope of the specific energy-efficient design to be evaluated.

(I.D) Analysis Tier (Tier 1 or Tier 2):

Tier 2 is required to track end uses and answer the study questions in Step I.B. However, a Tier 1 measurement plan is also included for illustrative purposes.

(I.E) Desired Accuracy of Results:

(±____%, or other criteria)

±5%. This tolerance is reasonably expected from the type of measurement equipment to be used, and it is deemed adequate for assessing the performance of the building.

(I.F) Estimated Budget for Performance Analysis:

DAS equipment:	$8,000
NREL staff time:	150 hours
NREL travel expense:	$4,000
Subcontracted data collection and analysis:	$15,000

(I.G) Dates of:

Site visits:	June 23–26, 2003 January 12–15, 2004
Monitoring period:	February 1, 2004 through January 31, 2005

(I.H) Basic Building Data:

Building description:
(Floor plan, gross area, floors, space uses, typical occupancy patterns)

See description in Section A.1. Floor areas are as follows (based on drawings):

- Main floor conditioned area = 1,264 ft^2
- Mechanical room loft = 103 ft^2
- Total conditioned floor area = 1,264 + 103 = 1,367 ft^2
- Unconditioned tower = 107 ft^2

Principal Building Function(s):
Principal building types are classified according to the commercial activities, which are types of business, commerce, or function carried on within each building (based on EIA 2003).
Indicate percent floor area for all that apply:

	Education		Health Care		Office		Religious Worship		Parking
	Food Sales		Lodging	**100%**	Public Assembly		Other Service		Other
	Food Service		Mercantile		Public Order and Safety		Warehouse and Storage		Vacant

Equipment Specifications:
(For all major energy-using equipment at the facility: number, sizes, models, energy ratings, etc.)

- PV array: Uni-Solar PV laminates PVL-128, PVL-64, PVL-87, and PVL-116; 8.702 kW total
- Inverters: SMA America, Sunny Boy model 2500U-D; 4 units
- Ground-source heat pump unit: ECONAR Energy Systems Corp., model Q18kW6T Air handler 1990 CFM

Pump pack GPP-2S25-1A, 14 GPM, 35-ft head, 490 W, 1/3 HP

- Electric duct heater: 10 kW
- Heat-recovery ventilation unit: Carrier, model HRV-CCLHU1330, 300 CFM
- Lights: 1,453 W total (1,103 W fluorescent, 350 W incandescent)
- Daylighting controller by Lutron, with microPS photosensor (linear response between 0 and 500 foot-candles [fc]) and MW-LC-2 lighting controller.
- Domestic water heater: A.O. Smith, model ELSF-30, 30 gal, 3 kW.

Utility Company(s) and Rate Schedule(s):
(Attach to this form)

Not applicable. This building has no energy bills directly associated with it. Electricity is supplied to the Science House building via an underground feed from the main museum building. The impact of this building on the museum's overall energy bill is not discernable from the data collected, and an analysis of energy costs based on a hypothetical billing arrangement was not a goal of this study.

All Relevant Building Drawings: (e.g., floor plans; elevations; electrical panel layouts; lighting plans; heating, ventilation, and air-conditioning [HVAC] plans; plumbing plans; outdoor lighting plans)
(Obtain at this time)

On-hand.

(I.I) Pre-Existing Performance Data
(Obtain at this time)

None available, because this is a new building.

A.3 – Measurement System Design

Steps II.A through II.E: A measurement plan for a Tier 1 analysis is shown in Table A-2 as an example, although this plan was not implemented. All standard metrics are included except **Net Facility Purchased Energy Cost**, which does not apply in this case, as explained above. A diagram of this measurement scheme is shown in Figure A-1.

The Tier 2 measurement plan, which was implemented, is shown in Table A-3. Several standard metrics were excluded (crossed off in Table A-3) for the following reasons:

- The **DHW Load** and **DHW System Efficiency** metrics had not yet been defined when the measurement system was designed.
- All cost metrics were excluded because this building has no energy bills directly associated with it. As mentioned in Section A.1, electricity is supplied to the Science House building via an underground feed from the main museum building. The impact of this building on the museum's overall energy bill is not discernable from the data collected, and an analysis of energy costs based on a hypothetical billing arrangement was not a goal of this study. (This also applies to the Tier 1 measurement plan.)
- Additional excluded metrics correspond to features that the Science House does not have.

Several user-defined metrics were added to the measurement plan. These are listed at the end of Table A-3. A diagram of this measurement scheme is shown in Figure A-2. A Campbell Scientific CR10X data logger was used to record the data.

Table A-2 Example Tier 1 Measurement Planning Form

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
1	**Gross Interior Floor Area**	Floor area	Drawings	One Time	N/A	N/A
2	**Functional Area** (Science House)	Item 18	N/A	One Time	N/A	N/A
3	**Total Facility Energy Use**	Items 2 and 3	N/A	N/A	N/A	**N/A**
4	**Facility Energy Production**	Merged output of four inverters	Wire between PV electrical panel and main electrical panel	Monthly	Utility-type watt-hour meter (WHM), bidirectional	1
5	**Net Facility Energy Use**	Energy to and from main museum building	Electrical feed entering Science House building from main museum building	Monthly	Utility-type WHM and demand meter, bidirectional	1
6	**Net Facility Electrical Demand**	See item 3	N/A	Monthly	N/A	N/A
7	**~~Net Facility Purchased Energy Cost~~**	N/A	N/A	N/A	N/A	N/A
8	**~~Net Facility Load Factor~~**	N/A	N/A	N/A	N/A	N/A
9	**Indoor Zone Temperature**	Thermostat setting(s)	Thermostat on interior wall	Monthly	Visual inspection and interview with building manager	N/A
10	**Outdoor Ambient Temperature** (also HDD and CDD)	Outdoor temperature	Minneapolis (MSP) weather station	Monthly	NCDC (2003) Climate Products	N/A

Step II.F: Determine the practicality of the measurements. The first site visit revealed that the actual configuration of circuit breakers in the main panel varied significantly from the drawings. Thus, the measurement plan was modified to accommodate these features. (Table A-3 has been revised to match the existing conditions.) In addition, the local building code does not permit the installation of watt-hour or current transducers in the main circuit breaker panel. To work around this constraint, an auxiliary electrical box was installed, and circuit wires were routed through this box for measurement purposes.

Step II.G: Estimate cost of DAS equipment and operation. The estimate determined in Table A-1, Step I.F, still seems realistic.

Step II.H: Calculate uncertainty of measurements.

All of the energy metrics consist of electrical power measurements. The accuracy specification of the WHMs is ±0.05% of full scale plus 0.45% of reading. The specification of the current transformers (CTs) is 1% of reading, for readings between 10% and 130% of full scale. Based on the procedure described in Appendix C, at full scale, the combined value of U95 is 1.1%, so U90 is 1.0%. This is well within the desired accuracy of ±5% (Step I.E). However, the percent error is larger at part-scale readings and becomes very large for small signals. Thus, care must be taken in the sizing of sensors. See further discussion in Section A.5.

Step II.I: Resolve cost and uncertainty with expectations (Steps I.E and I.F). At this stage, the expectations seem realistic.

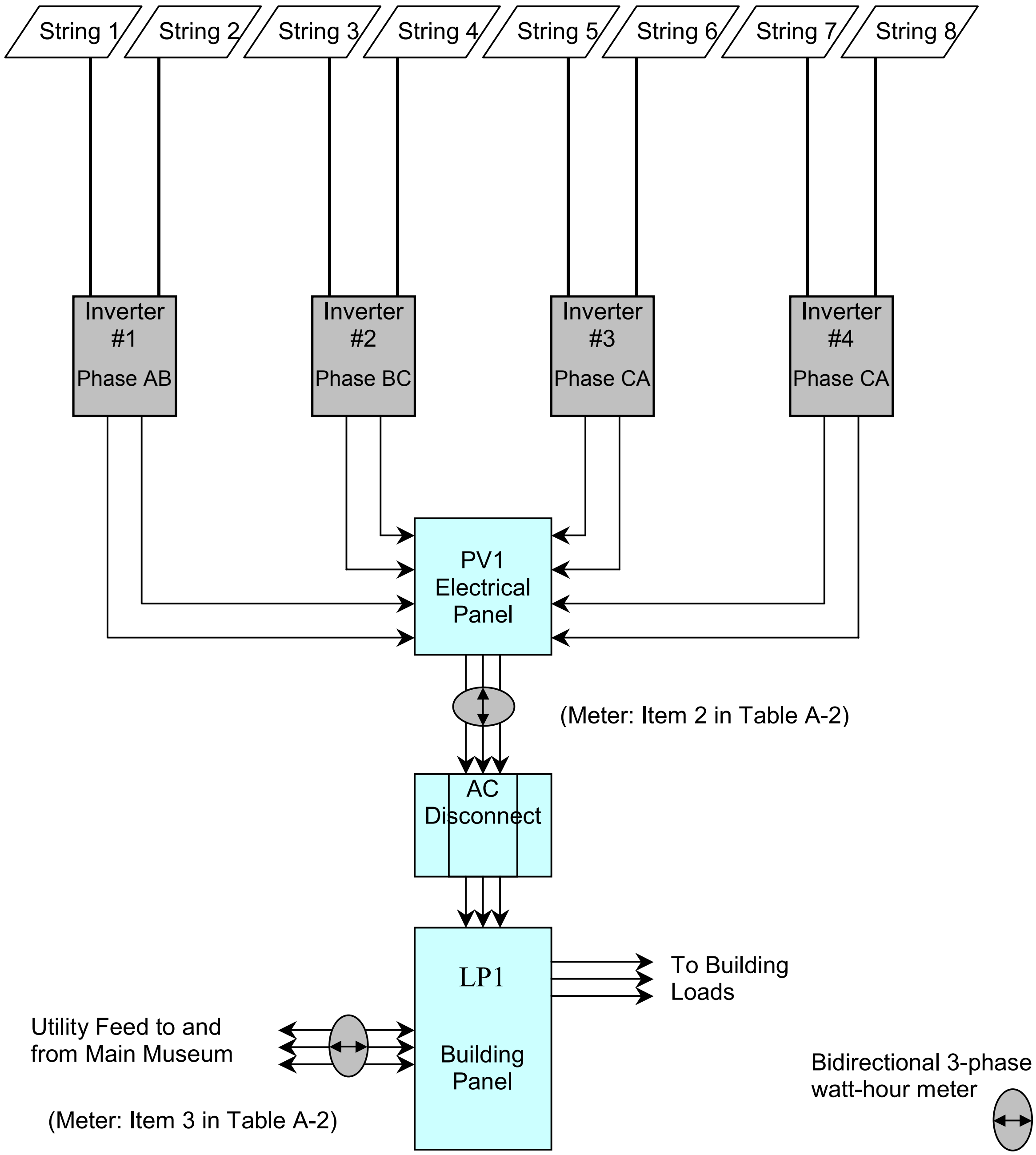

Figure A-1 Example diagram of Tier 1 measurement scheme

Table A-3 Example Tier 2 Measurement Planning Form

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
1	**Gross Interior Floor Area**	Floor area	Drawings	One time	N/A	N/A
2	**Functional Area** (Science House)	Item 1	N/A	N/A	N/A	N/A
3	**Installed Lighting Energy Use**	(a) Controlled lighting circuits (daylighting, occupancy); (b) Other lighting circuits	Distribution panel	15 min	Watt-hour transducers	2
4	**Plug-In Lighting Energy Use**	Number, power ratings, and schedules of lamps	Visual inspection and interview with building manager	Once	N/A	N/A
5	**Facade Lighting Energy Use**	Number, power ratings, and schedules of lamps	Visual inspection and interview with building manager	Once	N/A	N/A
6	**Building Lighting Energy Use**	Items 3 (includes item 4) and 5	N/A	N/A	N/A	N/A
7	**Heating Energy Use**	(a) Item 8; (b) Duct heater	(a) N/A (b) Distribution panel	(a) N/A (b) 15 min	(a) N/A (b) CT (Notes A, B)	(a) N/A (b) 1
8	**Cooling Energy Use**	(a) Heat pump unit energy, minus item 9a; (b) Supply air temperature (for heat/cool mode)	(a) Heat pump unit (b) Item 50	(a) 15 min	(a) Watt-hour transducer	(a) 1
9	**Air Distribution Energy Use**	(a) Main blower power; (b) Heat recovery ventilator power (blower, defrost)	(a) Inside heat pump unit; (b) Distribution panel	(a) 15 min (b) 15 min	(a) Watt-hour transducer; (b) CT (Notes A, C)	(a) 1 (b) 1
10	~~**Cold Storage Transfer**~~	N/A	N/A	N/A	N/A	N/A
11	**Other HVAC Energy Use**	Item 8	N/A	N/A	N/A	N/A
12	**HVAC Energy Use**	Items 7, 8, 9	N/A	N/A	N/A	N/A
13	**DHW Energy Use**	Electric water heater energy	Distribution panel	15 min	Watt-hour transducer	1

Table A-3 Example Tier 2 Measurement Planning Form (continued)

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
14	~~**DHW Load**~~	N/A	N/A	N/A	N/A	N/A
15	~~**DHW System Efficiency**~~	N/A	N/A	N/A	N/A	N/A
16	**Plug Loads Energy Use**	Energy in five plug load circuits; item 4	Distribution panel	15 min	Watt-hour transducer	1
17	~~**People-Mover Energy Use**~~	N/A	N/A	N/A	N/A	N/A
18	**Other Building Energy Use**	Energy use by watt-hour transducers	Line voltage connection to transducers	15 min	Watt-hour transducer	1
19	**Building Energy Use** (Science House)	Items 6, 12, 13, 16	N/A	N/A	N/A	N/A
20	**Building Energy Use Intensity** (Science House)	Items 2, 19	N/A	N/A	N/A	N/A
21	**Building Energy Use** (Shed)	Shed light and plug load power	Distribution panel	15 min	CT (Notes A, D)	1
22	~~**Building Purchased Energy Cost**~~	N/A	N/A	N/A	N/A	N/A
23	~~**Building Purchased Energy Cost Intensity**~~	N/A	N/A	N/A	N/A	N/A
24	**Building Electrical Demand**	Item 19	N/A	Monthly	N/A	N/A
25	**Building Electrical Demand Intensity**	Items 2, 24	N/A	Monthly	N/A	N/A
26	~~**Process Energy Use**~~	N/A	N/A	N/A	N/A	N/A
27	~~**Outdoor Energy Use**~~	N/A	N/A	N/A	N/A	N/A
28	~~**Cogeneration Fuel Use**~~	N/A	N/A	N/A	N/A	N/A
29	~~**Cogeneration Electrical Energy Output**~~	N/A	N/A	N/A	N/A	N/A

Table A-3 Example Tier 2 Measurement Planning Form (continued)

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
30	~~**Cogeneration Thermal Energy Output**~~	N/A	N/A	N/A	N/A	N/A
31	~~**Cogeneration Losses**~~	N/A	N/A	N/A	N/A	N/A
32	**PV Energy Production**	Four DC module voltages and currents	Four inverter inputs	15 min	Voltage probes Current shunts	4 4
33	~~**Wind Energy Production**~~	N/A	N/A	N/A	N/A	N/A
34	~~**Other Facility Electrical Energy Production**~~	N/A	N/A	N/A	N/A	N/A
35	**Electrical Generation System Losses**	Items 32, 38	N/A	N/A	N/A	N/A
36	~~**Thermal Energy Production**~~	N/A	N/A	N/A	N/A	N/A
37	~~**Produced Energy Storage Transfer**~~	N/A	N/A	N/A	N/A	N/A
38	**Facility Energy Production**	Power delivered by four inverters	PV panel	15 min	Watt-hour transducer	1
39	**Total Facility Energy Use**	Items 38, 39 (check energy balance with 19, 21)	N/A	N/A	N/A	N/A
40	**Net Facility Energy Use**	Power from and to main museum building	Distribution panel	15 min	Watt-hour transducers	2
41	~~**Net Facility Purchased Energy Cost**~~	N/A	N/A	N/A	N/A	N/A
42	**Total Facility Electrical Demand**	Item 3	N/A	Monthly	N/A	N/A
43	**Net Facility Electrical Demand**	Peak power from main museum building	(See item 38)	Monthly	N/A	N/A
44	**Net Facility Load Factor**	Items 40, 43	N/A	Monthly	N/A	N/A

Table A-3 Example Tier 2 Measurement Planning Form (continued)

Item	Performance Metric	Necessary Data	Point of Measurement or Source of Data	Recording Frequency	Measurement Equipment	
					Device(s)	Quantity
45	**Indoor Zone Temperature**	Air temperature	On wall near thermostat (2 measurements for redundancy)	15 min	Temperature/ humidity probe and TC	1 each
46	**Outdoor Ambient Temperature** (HDD and CDD)	Air temperature	North wall of shed (2 measurements for redundancy)	15 min	Temperature/ humidity probe and TC	1 each
User-Defined Metrics						
47	**Groundwater Temperature from Field**	Pipe temperature	Water supply pipe (need to locate)	15 min	TC	1
48	**Groundwater Temperature to Field**	Pipe temperature	Water return pipe (need to locate)	15 min	TC	1
49	**Indoor Relative Humidity Near Thermostat**	Relative humidity	On wall near thermostat	15 min	(See item 47)	N/A
50	**Supply Air Temperature**	Air temperature	In supply air duct	15 min	TC	1
51	**Return Air Temperature**	Air temperature	In return air duct or plenum	15 min	TC	1
52	**Mezzanine and Bathroom Lighting Energy Use**	Electrical circuit power	Distribution panel	15 min	CT (Notes A, B, F)	1
53	**Horizontal Solar Radiation**	Incident solar flux	On shed roof near PV array	15 min	Pyranometer	1
54	**Tilted Solar Radiation**	Incident solar flux	On PV array	15 min	Pyranometer	1

Notes:

A. Because of the limited number of pulse-input channels in the data logger for watt-hour nodes, CTs were used for several power measurements. This introduces an additional uncertainty because of variation in the line voltage and the power factor (for inductive loads only), which were not measured.

B. For resistive loads, such as this one, the power factor is 1.

C. For motors, the power factor should be measured.

D. For this mixed load (lights and miscellaneous plug loads), the CT does not give an accurate indication of power. However, this load is very small and occasional, so the error is slight.

E. This pump energy is included in the heat pump energy measurement (Items 5 and 6), so the inaccuracy of this measurement does not affect the energy balance.

F. This lighting energy is included in **Installed Lighting Energy Use** (Item 1), so the inaccuracy of this measurement does not affect the energy balance.

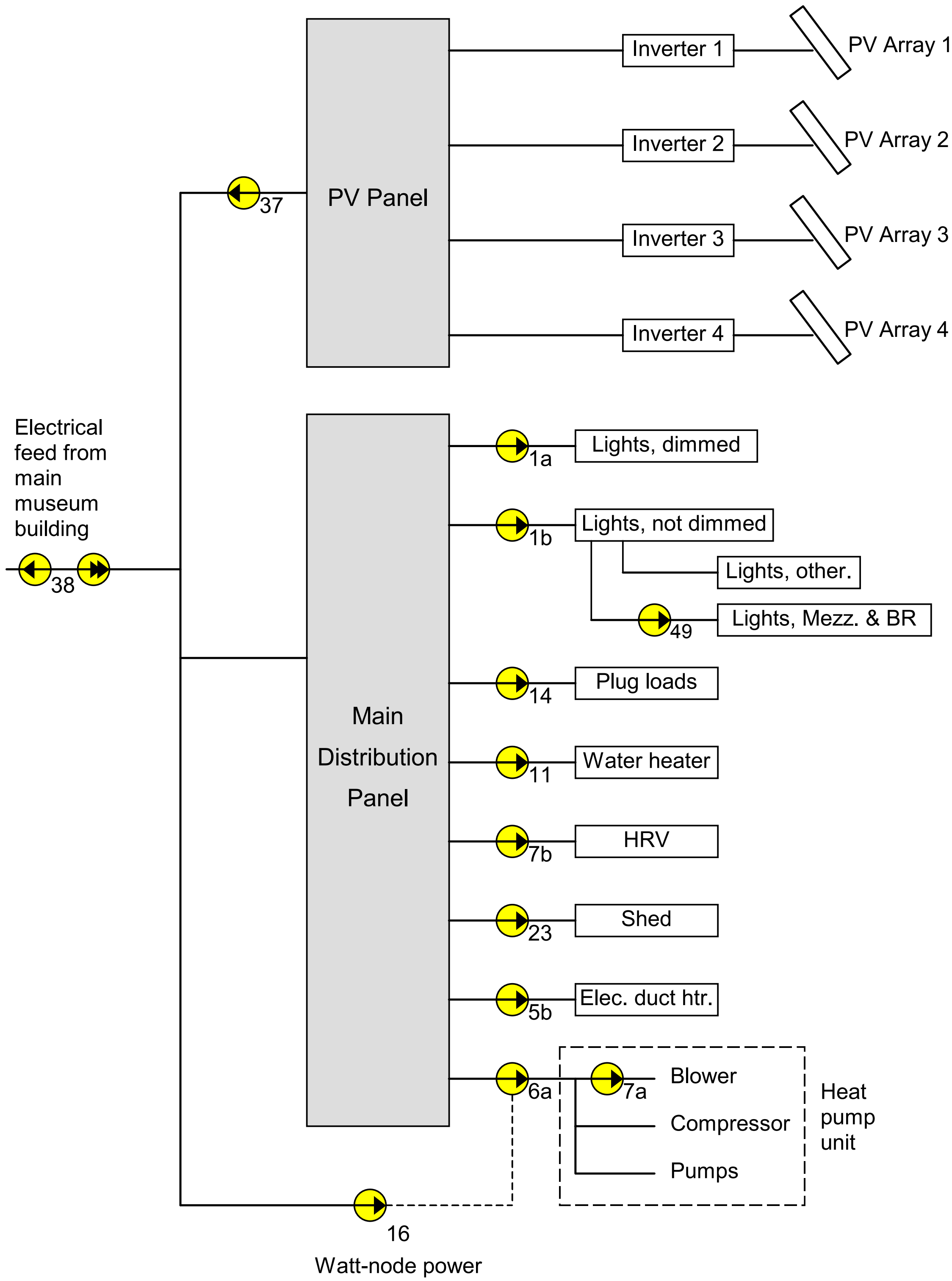

Figure A-2 Example diagram of Tier 2 measurement scheme.
Number labels correspond to rows in the Measurement Planning Form, Table A-3.

A.4 – Data Collection and Analysis

The DAS outlined in Table A.3 was installed in June 2003. Several problems were detected and resolved:

- Because the grid-connected inverters (see Table A-1, Item H) require electrical isolation of the DC side from the AC side, item 31 of the measurement plan (Table A.3) could not be implemented. Alternative voltage and current transducers, which feature electrical isolation, were not within the project budget. Thus, the metrics **PV Energy Production** and **Electrical Generation System Losses** were deleted from the measurement plan.

- The installation of a telephone line that enables remote retrieval of data from the data logger was delayed for several months.

- A watt-hour transducer failed shortly after it was installed. This is an unusual occurrence, and its cause was not determined. When the transducer was replaced with a new one, the problem did not recur.

All these DAS problems were resolved by January 2004. Because there are no utility bills for this building, the analysis months were chosen to correspond to calendar months. The analysis year was chosen as February 1, 2004 through January 31, 2005, beginning with the first complete month after the DAS problems were resolved.

Based on an interview with the building manager, the building has no plug-in lighting. The interview also revealed that the installed facade lighting was "almost never used," because the exhibit always closes before dark. Thus, the two metrics **Plug In Lighting** and **Facade Lighting** were assumed to be zero at all times.

Because the ground-source heat pump is used for heating, cooling, and air distribution, the guidelines of Section 6.5.3 were applied to disaggregate the energy use. Blower power was measured with a watt-hour transducer installed inside the heat pump cabinet. In the analysis, the following logic was applied:

- All the blower energy consumption was counted as **Air Distribution Energy Use.**

- In each 15-min time step when the blower was running and the supply air temperature was higher than the return air temperature, the unit energy consumption less the blower energy consumption was counted as **Heating Energy Use**.

- In each 15-min time step when the blower was running and the supply air temperature was lower than the return air temperature, the unit energy consumption less the blower energy consumption was counted as **Cooling Energy Use**.

- When the blower was not running, the standby unit energy consumption was counted as **Other HVAC Energy Use**.

Following the guidance of Section 6.4, redundant measurements were use to check the consistency of the data. Within this measurement system, the **Total Facility Energy Use** can be calculated in two ways:

(1) **Total Facility Energy Use** = **Building Energy Use (Science House)** + **Building Energy Use (Shed)**

(2) **Total Facility Energy Use** = **Net Facility Energy Use** + **Facility Energy Production**

The difference between these two calculations is shown in Table A-4 as Energy Balance Error. One source of error that was detected during this analysis was our failure to measure the energy used by the watt-hour transducers, which draw their power directly from the three phases of the voltage bus without going through one of the circuit breakers. This measurement was subsequently included in the measurement plan (Table A-3, Item 16) and applied retroactively. The source of the remaining energy balance error is not known. However, the error is within the tolerance of the watt-hour transducer used to measure the **Net Facility Energy Use**. This transducer was sized to accommodate the 125-amp rating of the main circuit breaker. This size turned out to be much larger than needed. In retrospect, the transducer should have been sized for the expected peak load, based on the appliances in the building.

During July and August 2004, a failure occurred in one of the three phases of the watt-hour transducer measuring the **Facility Energy Production** (the AC power from the PV system). Two possible methods for estimating the missing data series are:

(1) Correlate the **Facility Energy Production** to the **Tilted Solar Radiation**, and use the correlation to estimate the missing data.

(2) Determine the average energy balance error during the other 10 months; assume this value to hold during the failure period; calculate the **Facility Energy Production** as **Total Facility Energy Use** – **Net Facility Energy Use** – average energy balance error.

When method 1 was used, the resulting energy balance error was significantly larger for July and August than at other times. This outcome suggests that method 2 is more accurate. Thus, method 2 was used to estimate the missing data during July and August.

A.5 – Results

Monthly and annual values of all measured metrics are shown in Table A-4. The data indicate that the PV system produces more energy (8,454 kWh/yr) than the Science House building consumes (5,877 kWh/yr). Monthly average values of end-use loads and PV production are shown in Figure A-3. The **Facility Energy Production** (PV) follows the expected seasonal cycle. The largest end use is **Heating Energy Use**, which also follows the expected seasonal cycle. The **Cooling Energy Use**, which is much smaller than the **Heating Energy Use**, is significant only from June through September. The **Lighting Energy Use** is modest because the daylighting design is so effective.

The peak load occurred on January 5, 2005. Energy use on this day is shown in Figure A-4. The peak load was heavily influenced by the duct heater, which operates only rarely. Similar scenarios also occurred on single days in May and November. Because the indoor temperature dropped sharply each time the duct heater came on, we suspect that a building occupant left an outside door open. This would have initiated the sharp drop in indoor temperature and engaged the second stage of the thermostat, which turns on the duct heater. Unfortunately, the demand charges for 3 months were determined by such unnecessary events, and remedial actions should be considered.

Many of the monthly values of the **Net Facility Load Factor** shown in Table A-4 are negative, and the values that are positive are small. These numbers are unusual in common practice, but they are characteristic of buildings that are near zero energy or energy producing, as this building is. This metric calls attention to issues of utility supply and demand for buildings with large amounts of on-site energy generation relative to there size.

The uncertainty of the type of watt-hour meter (WHM) used in this study is analyzed in Section C.9.2 (Appendix C). That analysis shows that the errors associated with pulse counting are negligible. Thus, in this example, we apply the percent error specifications directly:

WHM: ±0.05% of full scale plus 0.45% of reading.
CTs: ±1% of reading, for readings between 10% and 130% of full scale.

The uncertainty of each WHM measurement is analyzed in Table A-5. The first four rows show that the percent error grows from ±1% at full scale to ±4.7% at 1% of full scale. The "Average % of Full Scale" column shows that the average operating point of the 10 WHMs ranged from ±0.1% to ±8.9%. The "Peak % of Full Scale" column shows that WHMs #2 and #3 were sized rather appropriately, but the other WHMs were oversized. Ideally, the WHMs should be sized so that peak load is about 100% of full scale. This oversizing of the WHMs led to large uncertainties in the measurements, as shown in the "Net U90 %" column.[14]

The uncertainty of the metrics derived from these measurements is shown in Table A-6. Some of the end-use metrics have large percent uncertainties. As a lesson learned, smaller CTs should have been used for these measurements. The uncertainty of the **Total Facility Energy Use** is ±5.2%, which is consistent with the goals of the study. The uncertainty of the **Facility Energy Productio**n is only ±1.2%; this was measured with WHM #3, which was well sized. Table A-6 also shows that the Energy Balance Error is within the uncertainty of the measurements.

References

NCDC (2003). Climate Products. http://lwf.ncdc.noaa.gov/oa/ncdc.html. Last modified August 25, 2003. (Accessed September 26, 2003.) Asheville, NC: National Climatic Data Center.

[14] All of the average power levels are less than 10% of full scale, where the manufacturer has not specified the accuracy. We applied the 1% of reading specification to these numbers as a best estimate. Although the percent error for the small measurements may be much higher than estimated, these have a small effect on the much larger totals.

Table A-4 Monthly and Annual Metrics for the Sample Project

METRIC	Units	Month												ANNUAL
		Feb 04	Mar 04	Apr 04	May 04	Jun 04	Jul 04	Aug 04	Sep 04	Oct 04	Nov 04	Dec 04	Jan 05	
Gross Interior Floor Area (Science House)	ft^2	1367												
Functional Area (Science House)	ft^2	1367												
Installed Lighting Energy Use	kWh	10.4	13.5	19.0	22.7	39.3	29.4	43.1	15.6	14.7	14.2	13.4	15.0	250.4
Plug-In Lighting Energy Use	kWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Facade Lighting Energy Use	kWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Building Lighting Energy Use	kWh	10.4	13.5	19.0	22.7	39.3	29.4	43.1	15.6	14.7	14.2	13.4	15.0	250.4
Heating Energy Use	kWh	684.3	511.6	191.0	93.6	6.0	0.0	0.0	0.0	78.5	447.9	783.7	974.0	3770.6
Cooling Energy Use	kWh	0.0	0.0	0.0	0.8	33.1	105.1	108.8	77.7	0.0	0.0	0.0	0.0	325.5
Air Distribution Energy Use	kWh	54.9	55.2	61.3	70.7	70.7	102.6	73.7	44.9	28.8	49.2	58.9	72.9	743.6
Other HVAC Energy Use	kWh	1.1	1.6	4.5	6.0	6.0	6.3	6.4	6.9	6.8	2.6	1.0	0.9	50.1
HVAC Energy Use	kWh	740.4	568.4	256.7	171.1	115.8	214.0	188.8	129.6	114.1	499.6	843.5	1047.8	4889.9
DHW Energy Use	kWh	0.0	0.0	0.0	0.0	11.5	52.2	136.3	50.8	3.4	11.4	0.0	0.0	265.6

Table A-4 Monthly and Annual Metrics for the Sample Project (continued)

METRIC	Units	Month												ANNUAL
		Feb 04	Mar 04	Apr 04	May 04	Jun 04	Jul 04	Aug 04	Sep 04	Oct 04	Nov 04	Dec 04	Jan 05	
Plug Loads Energy Use	kWh	5.0	17.6	37.8	36.1	31.8	61.8	91.7	31.9	11.6	12.4	8.5	16.4	362.5
Other Building Energy Use **	kWh	8.6	9.2	8.9	9.2	8.9	9.2	9.2	8.9	9.2	8.9	9.2	9.2	108.3
Building Energy Use (Science House)	kWh	764.3	608.7	322.3	239.1	207.3	366.5	469.1	236.8	153.1	546.5	874.6	1088.3	5876.7
Building Energy Use (Shed)	kWh	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.3
Building Energy Use Intensity (Science House)	kWh/ ft^2													4.30
Building Electrical Demand	kW	3.1	2.5	2.0	10.0	4.5	4.0	3.3	3.7	4.1	11.3	3.6	11.7	11.7
Date and time of Building Electrical Demand		2/3, 21:45	3/30, 11:00	4/27, 12:00	5/13, 08:45	6/11, 09:45	7/1, 12:45	8/31, 12:45	9/5, 13:30	10/20, 08:15	11/17, 04:00	12/19, 17:15	1/10, 14:30	1/10, 14:30
Building Electrical Demand Intensity	kW/ft^2	2.24	1.83	1.44	7.29	3.29	2.93	2.39	2.74	2.97	8.23	2.66	8.55	8.55
Facility Energy Production	kWh	471.8	678.0	1029.3	952.6	1022.5	1085.0	869.0	851.2	464.6	430.5	314.9	285.1	8454.4
Total Facility Energy Use	kWh	764.3	608.7	322.5	239.1	207.3	366.6	469.1	236.8	153.1	546.5	874.6	1088.3	5876.9
Net Facility Energy Use	kWh	292.5	-69.3	-706.9	-713.4	-815.2	-718.4	-399.9	-614.3	-311.5	116.0	559.7	803.2	-2577.5
Total Facility Electrical Demand	kW	3.1	2.5	2.0	10.0	4.5	4.0	3.3	3.7	4.1	11.3	3.6	11.7	11.7

Table A-4 Monthly and Annual Metrics for the Sample Project (continued)

METRIC	Units	Month												ANNUAL
		Feb 04	Mar 04	Apr 04	May 04	Jun 04	Jul 04	Aug 04	Sep 04	Oct 04	Nov 04	Dec 04	Jan 05	
Date and time of Total Facility Electrical Demand		2/3, 21:45	3/30, 11:00	4/27, 12:00	5/13, 08:45	6/11, 09:45	7/1, 12:45	8/31, 12:45	9/5, 13:30	10/20, 08:15	11/17, 04:00	12/19, 17:15	1/10, 14:30	1/10, 14:30
Net Facility Electrical Demand	kW	3.1	2.1	1.6	9.7	3.2	2.4	2.9	2.4	3.7	10.9	3.6	11.3	11.3
Date and time of Net Facility Electrical Demand		2/3, 21:45	3/12, 03:00	4/12, 20:30	5/13, 08:45	6/11, 09:45	7/21, 18:45	8/6, 19:45	9/9, 19:45	10/20, 08:15	11/17, 04:00	12/19, 17:15	1/10, 14:30	1/10, 14:30
Net Facility Load Factor	--	0.137	-0.045	-0.623	-0.099	-0.358	-0.407	-0.187	-0.358	-0.112	-0.015	0.207	0.096	-0.026
Indoor Zone Temperature	°F	65.2	65.1	65.2	65.8	67.7	72.6	71.7	72.3	65.2	65.7	65.1	64.7	67.2
Outdoor Ambient Temperature	°F	24.8	37.1	51.0	58.2	66.9	73.5	67.6	68.7	50.8	39.3	23.7	17.1	48.2
HDD (Base 65°F)	°F-days	1085	866	432	220	50	7	38	38	440	771	1281	1485	6714
CDD (Base 50°F)	°F-days	0	16	113	264	508	728	546	562	109	3	0	0	2848
CDD (Base 65°F)	°F-days	0	0	12	8	108	270	119	150	0	0	0	0	667
Energy Balance Error	kWh	22.6	20.1	19.6	18.6	29.1	19.0	18.9	12.9	12.6	16.2	21.6	18.0	229.2
User-Defined Metrics														
Groundwater Temperature from Field*	°F	47.2	48.2	50.8	52.9	58.7	61.0	60.8	61.7	53.4	51.0	48.2	46.5	54.0

Table A-4 Monthly and Annual Metrics for the Sample Project (continued)

METRIC	Units	Month												ANNUAL
		Feb 04	Mar 04	Apr 04	May 04	Jun 04	Jul 04	Aug 04	Sep 04	Oct 04	Nov 04	Dec 04	Jan 05	
Groundwater Temperature to Field*	°F	42.4	43.4	46.2	48.7	60.2	64.0	64.5	65.3	47.8	45.3	42.8	41.2	51.9
Indoor Relative Humidity Near Thermostat	%	26.0	30.6	33.5	43.9	53.7	55.9	51.6	52.7	45.4	39.9	28.9	23.3	42.0
Supply Air Temperature*	°F	89.7	84.7	80.4	78.2	62.5	63.4	60.9	63.0	78.2	84.8	89.0	91.4	75.9
Return Air Temperature*	°F	73.4	70.7	68.5	67.6	67.8	72.8	71.4	73.1	67.0	70.9	72.8	73.7	70.5
Mezzanine and Bathroom Lighting Energy Use	kWh	8.0	8.5	8.8	9.5	10.5	10.9	11.3	9.2	8.9	8.9	9.0	8.8	112.4
Horizontal Solar Radiation	kWh/m^2	66.4	89.9	146.6	145.0	168.8	171.8	140.4	119.4	61.4	46.1	32.9	43.0	1231.7
Tilted Solar Radiation	kWh/m^2	78.5	102.0	158.2	146.1	167.5	174.5	147.7	140.2	76.5	67.5	49.5	62.1	1370.2

* Temperatures averaged only while heat pump is running.

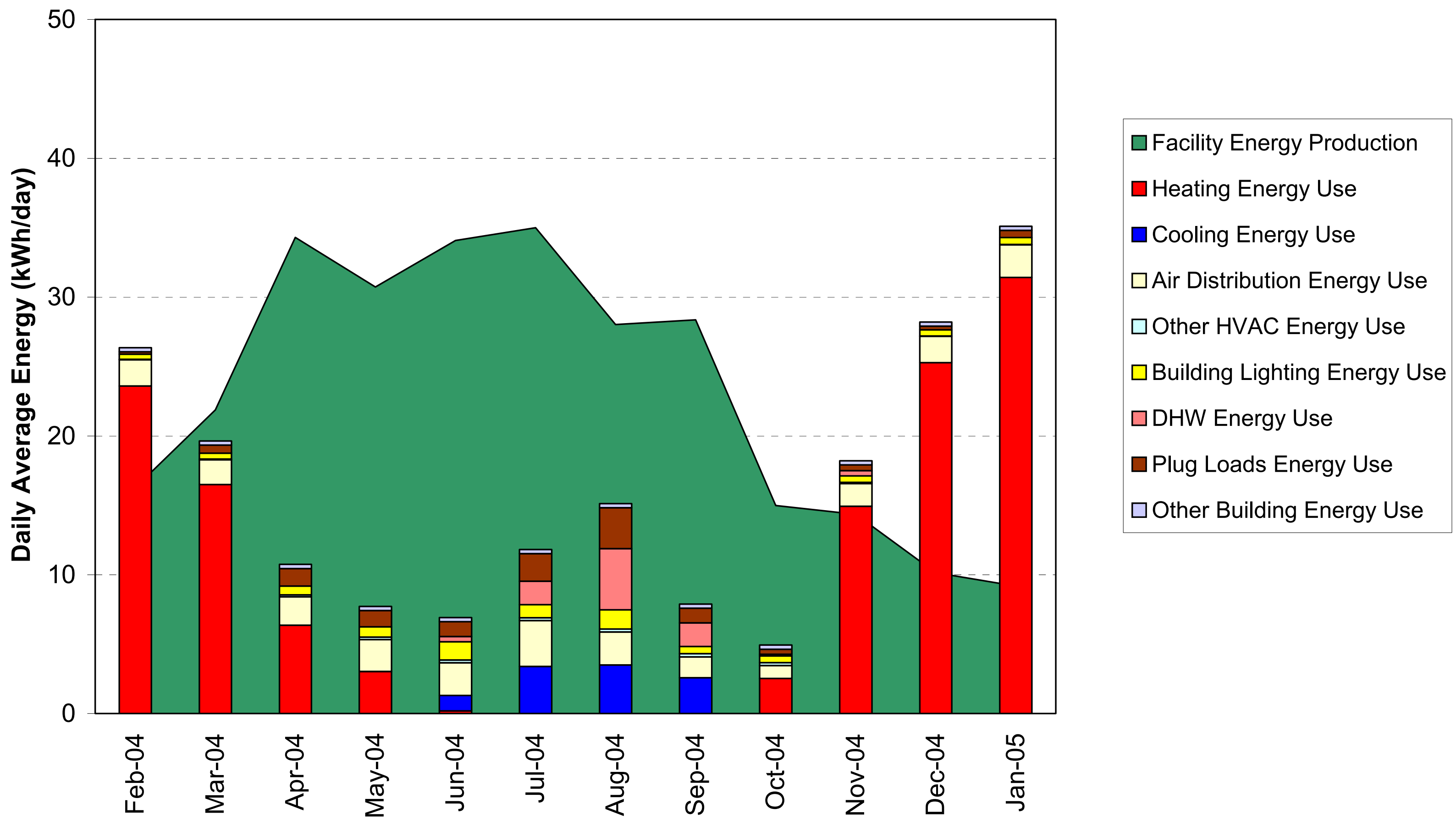

Figure A-3 Average daily end-use energy consumption and PV energy production, by month

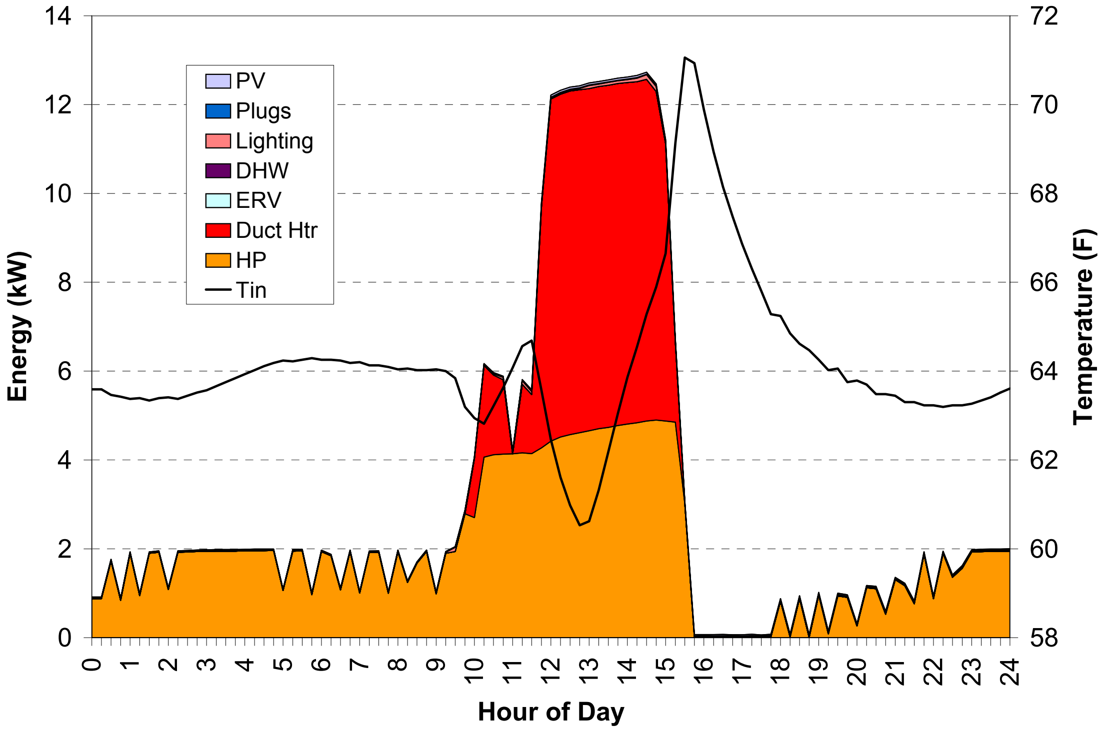

Figure A-4 Illustration of the day on which the peak demand occurred.

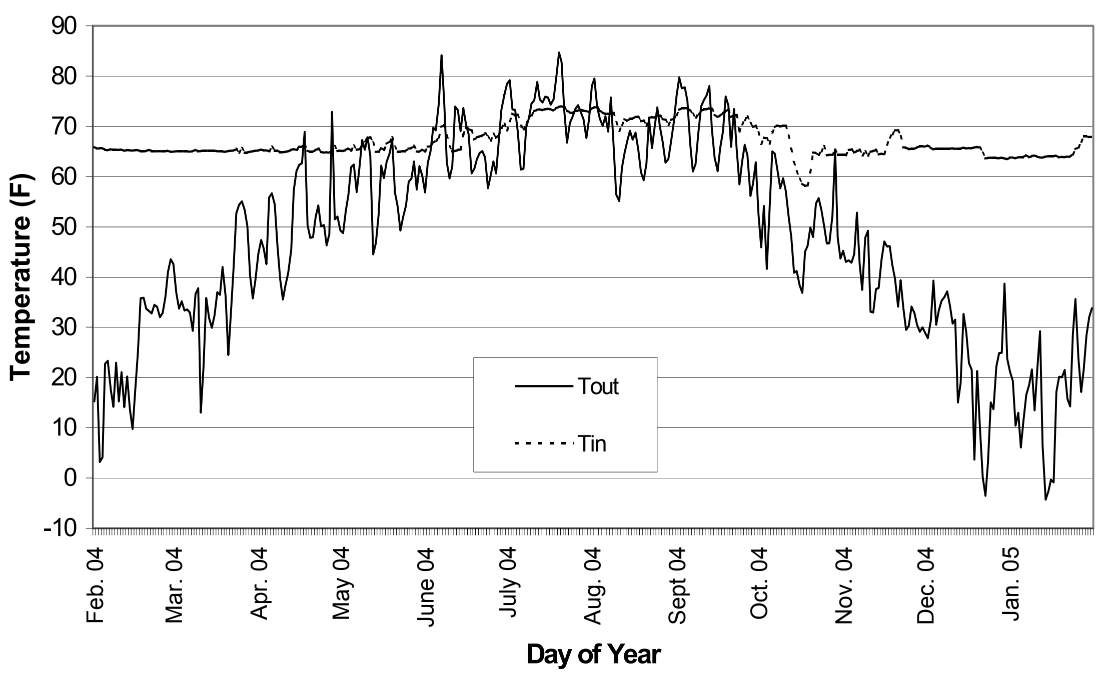

Figure A-5 Daily average indoor and outdoor temperatures for the analysis year

Table A-5 Uncertainty Analysis of WHM Measurements

Ref. Case or WHM #	CT size A	(3-Phase) FS Power kW	Usage kWh/yr	Average Power kW	Average % of Full Scale	Peak Power kW	Peak % of Full Scale	WHM U95 kW	CT U95 kW	Net U95 kW	Net U90 kW	Net U90 %	Net U90 kWh/yr
Full Scale	30	10.8	94608	10.800	100.0			0.054	0.108	0.121	0.103	1.0	899
1/2 scale	30	10.8	47304	5.400	50.0			0.030	0.054	0.062	0.052	1.0	459
1/10 scale	30	10.8	9461	1.080	10.0			0.010	0.011	0.015	0.013	1.2	111
1/100 scale	30	10.8	946	0.108	1.0			0.006	0.001	0.006	0.005	4.7	45
1	150	54.0	4589	0.524	1.0	11.280	20.9	0.029	0.005	0.030	0.025	4.8	222.0
2	30	10.8	6937	0.792	7.3	6.912	64.0	0.009	0.008	0.012	0.010	1.3	89.1
3	30	10.8	8454	0.965	8.9	7.044	65.2	0.010	0.010	0.014	0.012	1.2	102.1
4	30	10.8	111	0.013	0.1	0.564	5.2	0.005	0.000	0.005	0.005	36.6	40.6
5	30	10.8	140	0.016	0.1	0.356	3.3	0.005	0.000	0.005	0.005	29.1	40.8
6	30	10.8	362	0.041	0.4	1.976	18.3	0.006	0.000	0.006	0.005	11.5	41.7
7	50	18.0	4406	0.503	2.8	4.896	27.2	0.011	0.005	0.012	0.010	2.1	91.8
8	30	10.8	266	0.030	0.3	2.684	24.9	0.006	0.000	0.006	0.005	15.5	41.3
9	30	10.8	300	0.034	0.3	0.688	6.4	0.006	0.000	0.006	0.005	13.8	41.4
10	30	10.8	444	0.051	0.5	0.496	4.6	0.006	0.001	0.006	0.005	9.5	42.1

Table A-6 Uncertainty Analysis of Metrics

Metric	Annual Value (kWh)	U90 (kWh)	U90 %	
Building Lighting Energy Use	250.4	81.4	32.5	
Heat Pump	4405.9	91.8	2.1	
Duct Heater	40.1	2.0	5.0	*
ERV	443.9	42.1	9.5	
HVAC Energy Use	4889.9	135.9	2.8	
DHW Energy Use	265.6	41.3	15.5	
Plug Loads Energy Use	362.5	41.7	11.5	
Other Building Energy Use	108.3	5.4	5.0	*
Building Energy Use (Science House)	5876.7	305.7	5.2	
Building Energy Use (Shed)	0.3	0.0	5.0	*
Total Facility Energy Use (1)	5877.0	305.7	5.2	
Facility Energy Production	8454.4	102.1	1.2	
Net Facility Energy Use	-2577.4	407.8	15.8	
Total Facility Energy Use (2)	6106.0	235.1	3.9	
Energy Balance Error	229.0	540.8		

Note:

* Uncertainty is estimated.

Appendix B – Description of Monitoring Equipment

This appendix contains a brief introduction to measurement techniques and equipment—it is not meant to be a definitive source of information. The reader is encouraged to conduct further research into these techniques and equipment if there are additional questions after reading this section. For additional information on building energy monitoring equipment and methods, see the *ASHRAE Handbook of Fundamentals* (2005), *ASHRAE Guideline 14* (2002), and *International Performance Measurement and Verification Protocol, Volume I* (2002).

Maintain the calibration of all instruments according to the manufacturers' recommendations. Some instruments must be field calibrated after installation. Instruments may require recalibration or replacement during long monitoring periods. Maintain a record of all instrument calibrations during the monitoring period.

B.1 – Data Logger

The data logger is the most important piece of equipment in the data acquisition system (DAS). The options are usually to use small, self-contained units that house the sensors and data logger, or to use one or more central data loggers. Although the self-contained units are easy to install, they do not allow remote access to the data, they must be synchronized with other units, and they generate multiple data files. A central data logger can be expensive; however, it will usually pay for itself in saved time during data collection and analysis. Some building automation systems (BAS) can log and store data, but their use as data loggers should be analyzed carefully. Most BAS are not designed to be data loggers; therefore, problems with precision, scan rate, storage, retrieval, or reliability may arise. The following features are key in a central data logger:

- *Reliability:* The data logger must be dependable and robust. If the data logger fails, all the data will be lost for that period; the data collected up to the point of failure may be lost as well. A reliable data logger usually pays for itself by reducing maintenance costs and avoiding lost data.
- Memory: The data logger must be able to store the collected data for long periods in case there are times when the data cannot be retrieved. Recording time-series data can create large data files. Ideally, a data logger should be able to store many months of data without running out of memory.
- Communications: Most data loggers have, at a minimum, an RS232 port for direct connection to a computer. For long-term data monitoring, remote communication capabilities that allow data retrieval, data logger programming, and data logger troubleshooting are usually preferable. For building applications, remote access is usually through a telephone modem, a cell phone modem, or an Internet connection.
- Data Storage Format: The format of the data storage should be straightforward and easy to work with. Some systems have storage formats that are difficult to process and may even result in lost data. The easiest format is usually a comma-delimited text file with a date and time stamp for each set of readings.
- Versatility: A good data logger will be flexible enough to handle many types of sensors and ranges of inputs. Sensor outputs may be voltage, current, or pulses. The data logger should also be able to supply excitation outputs to power sensors. Its scan rate should be an order of magnitude greater than the dynamics of the system being monitored. The data logger should also be able to expand to handle many inputs.
- Programmability: Many data loggers include built-in functions for converting signals from sensors into convenient engineering units. Examples include simple mathematical expressions, complex thermocouple (TC) conversions, and combining flow and temperatures to calculate

energy flow (e.g. “Btu meter”). Programming the data logger to perform these tasks reduces the amount of data post processing and facilitates quick data assessments.

- Capability for Backup Power: The data logger should be able to operate for at least 2–4 weeks on backup power in case of a power outage or if it is inadvertently unplugged.

B.2 – Alternating Current Power Measurements

In alternating current (AC) systems, the voltage and current waveforms vary with time over a cycle. Thus, the power is also cyclic, and the desired measurement is the *averag*e power over a cycle. The type of equipment needed to measure AC power depends on the current waveform, i.e., whether it is a sine wave and whether it is in phase with the voltage waveform. A power transducer is a device that can accurately measure the average power in any situation, regardless of the type of current waveform. However, in some cases a simpler method is recommended. Generally there are three cases to consider, depending on the type of load.

1. *Case 1: Resistive loads.* In loads that behave as resistors (with $E = I \cdot R$), such as incandescent lights and electrical resistance heaters (water heater, duct heater, electric baseboard, etc.), the current is a sinusoid in phase with the voltage. In this case, the recommended measurement scheme is to monitor the root mean square (RMS)[15] voltage and RMS current, and compute the power as

   Power = (RMS voltage) × (RMS current).

2. *Case 2: Sinusoid out of phase.* If the current is a sinusoid that is out of phase with the voltage, such as electric motors (blower, pump, compressor, etc.), the formula for the power is:[16]

   Power = (RMS voltage) × (RMS current) × (power factor).

   If the power factor were a constant, it would be sufficient to measure the power factor once, monitor the RMS voltage and RMS current, and use this formula. However, any changes in the loading of a motor, such as dirt buildup on an air filter, corrosion of pipes, or changes in heat pump operating temperatures, can cause the power factor to vary. Therefore, the recommended measurement scheme is to use a power transducer.

3. *Case 3: Nonsinusoidal current.* If the current is an irregular (nonsinusoidal) waveform, such as fluorescent lights, dimmer controls, or other loads, a power transducer must be used.

AC current can be measured by a split core CT that fits around an existing wire without interrupting it (the wire does not need to be cut to install the device). When a power transducer is used, a similar type of CT is attached to the power transducer, along with a voltage connection. If electrical energy flows in both directions in the same wire, two sets of unidirectional CTs and watt-hour transducers, or one bidirectional device, may be required. The CTs should be sized for maximum expected load and not the breaker size. Breakers usually have a higher rating than the maximum load on the circuit. Oversized CTs will lower the accuracy of the measurements. Many CTs have a linear range of response between 10% and 130% of their rated capacity.

AC voltage should be monitored continuously with an AC voltage transducer if it is required for power calculations. Even though the grid voltage has a fixed nominal value, the actual voltage varies significantly with changing load conditions. A typical bus voltage variation is ±5%. The electric utility company may quote a more specific tolerance.

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[15] RMS is the square root of the average value of the square of the quantity. This is a special type of average that applies in power calculations. Devices are available that measure RMS voltage and RMS current.
[16] The power factor is the cosine of the phase angle between the voltage and current waveforms, when both waveforms are sinusoids.

Three-Phase Power Systems

If three-phase electrical power needs to me measured, it will require three-phase power transducers. The power transducer should be selected based on the wiring configuration (three-phase/three-wire or three-phase/four-wire). Various three-phase power transducer models feature watt, volt-ampere, power factor, and watt-hour outputs; various response times; and the ability to accommodate chopped or distorted voltage and current waveforms within the accuracy specifications.

B.3 – Direct Current Power Measurements

CTs, and thus the type of power transducer that is recommended for AC power measurements (Section B.2), do not work with direct current (DC). Two general classes of alternative methods are available:

- *Electrically coupled.* The DAS shares a common electrical ground with the system being monitored. Measurement apparatus is relatively inexpensive.
- *Electrically isolated.* The DAS is electrically isolated from the system being monitored. Measurement apparatus is more expensive. This requirement may occur, for example, in a grid-connected photovoltaic (PV) system, where the design of the inverter requires that the DC power circuitry be isolated from ground.

When DC voltage and current are measured separately, the instantaneous DC power is the product of the current times the voltage. Often, the DC power will have some periodic components or other fluctuations in it because of the pulsating nature of current or voltage waveforms in DC systems introduced by rectifiers, inverters, and so on. In such cases, the sampling rate must be high enough to capture and analyze the fluctuations, and the average DC power can be calculated for any desired averaging period.

Electrically Coupled Systems

A voltage divider is recommended to measure DC voltage in electrically coupled systems. This consists of a simple network of two precision resistors in series, which reduces the range of voltages in the system to the range of voltages accepted by the DAS. The corresponding conversion factor is used to interpret the measurements for data analysis.

A shunt resistor is recommended to measure DC current in electrically coupled systems. A precision low-resistance resistor is placed in series with the circuit to be monitored. The resistance value is chosen to convert the range of currents in the system to the range of voltages accepted by the DAS. The power rating of resistor must also be chosen to accommodate the amount of power consumed (and thus heat generated) in the shunt resistor.

Electrically Isolated Systems

One type of DC watt transducer employs an external Hall-effect[17] current sensor to measure the DC power. In some cases, for low current systems (up to 20 A) there is no need for an external current sensor because the watt transducer comes with its own internal current sensors. Hall-effect current sensors are more complex and expensive than simple current shunts. However, the Hall-effect technology is a noncontact method of current measurement that provides electrical isolation. For the same reason, electrically isolated voltage transducers are much safer to use than inexpensive voltage dividers. The lack of electrical isolation may damage the DAS in case of overvoltage events, lightning strikes, and other mishaps. Among other benefits, the Hall-effect current sensors come in a split-core configuration. This allows the power measurement equipment to be installed in just a few minutes without breaking the

[17] Hall-effect current measurement is a noncontact technique that measures the magnetizing effects of current flowing in a conductor.

existing power lines. In field applications, problems have been experienced with maintaining the calibration of Hall-effect sensors. One problem is the temperature sensitivity of the calibration.

Another option is to use DC voltage and current transducers that achieve electrical isolation without the use of the Hall effect. Some are unidirectional and some are bidirectional. Typical accuracies are ±0.25%–1% of full scale plus 0.25% of reading. As of this writing, prices are about $200–$400 per sensor.

B.4 – Temperature Measurements

Temperature measurements for building energy evaluation purposes are less difficult than with many engineering applications because accuracy requirements are typically not as tight, environmental conditions are not extreme, and response times can be longer. The most common devices for measuring temperatures for building evaluation with a DAS are thermocouples (TC), thermistors, resistance temperature detectors, and integrated circuit temperature sensors. The choice of sensor will most likely depend on the application, the price, the availability, and the technician's experience. The required accuracy and time response of the measurements will depend on the use. If the temperature is used to indicate a condition, accuracy is probably not very important. If the temperature is used to calculate energy flows, the accuracy and time response may be important, depending on the desired accuracy of the analysis. To ensure the best measurement, several issues must be addressed with any device for measuring temperature. Ensure that the device is calibrated according to the manufacturer's recommendations and that the data logger is properly programmed to read the sensor output. The location of the sensor is probably the most critical decision. For any temperature measurement, the sensor should be located such that it represents the temperature of the desired object or volume of fluid. This means that it must be located away from local heat sources and heat sinks.

For dry-bulb air temperature measurements, radiation shielding should be used if surrounding surfaces are at significantly different temperatures or if it is in the direct sunlight. The shielding should be carefully implemented; improper shielding can introduce errors in the measurement. Aspirating the temperature sensor can improve the accuracy by increasing the convection heat transfer from the gas to the sensor. For an outside air temperature, the sensor should be located out of the direct sun and inside a radiation shield to eliminate exposure to direct or reflected solar radiation. Room air temperature sensors are sometimes placed next to the thermostat temperature sensor to measure the temperature used for controlling the heating, ventilating, and air-conditioning (HVAC) system. Measuring the average room air temperature can be estimated by thoughtful placement of a single sensor in the middle of the room or inside the return air duct for a well-mixed room. The return air duct sensor has a drawback in that it will not have the same representation of the room air temperature when the fan system is off. Multiple sensors may also be used, in which case the average temperature is calculated as a volume-weighted average of all the sensors.

Fluid temperatures in a duct or a pipe can be measured with multiple techniques. For low accuracy requirements, the duct temperature can be measured by one temperature sensor placed in the central region of the duct. Accurate measurements will require multiple temperature sensors and a mass-flow weighted averaging of the readings. Fluid temperatures in a pipe can be measured by embedding a temperature sensor in a thermal well in the pipe or a sensor strapped to the outside of the pipe. Neither technique responds quickly to changing fluid temperatures or represents the true average fluid temperature; therefore, the accuracy of the measurement techniques should be accounted for.

Other temperatures that are commonly monitored in building energy evaluations are the dew-point temperature, wet-bulb temperature, and the mean-radiant temperature. The dew-point and wet-bulb temperatures can be measured with special sensors or calculated from the measurement of the dry-bulb temperature, relative humidity (RH), and pressure (for wet-bulb temperature). The mean-radiant temperature can be measured with a mean-radiant temperature globe.

More information on temperature sensors and measurement techniques can be found in manufacturers' data, instrumentation texts, and the references mentioned at the beginning of this Appendix.

B.5 – Solar Radiation

The simplest method for measuring the solar radiation is with a pyranometer, which measures the total solar radiation on a surface. Two types of pyranometers are in common use:

- *Thermopile*. This instrument consists of a series of TCs that detects a temperature difference caused by the solar radiation. The thermopile is the more accurate and more expensive of the two types.
- *Photovoltaic*. This instrument includes a PV cell, and the measurement is based on the electrical response of the cell to the solar radiation. The most common type of sensor uses a photodiode to measure the incident solar radiation. The output of the photodiode is not uniform across the solar spectrum, but the error is small. Because of this nonuniform response, these instruments are not recommended for use under artificial light, under plant canopies, or where there is significant reflected light. However, this less expensive type of instrument is adequate for completing this procedure.

The global horizontal solar radiation is the most useful measurement. Most simulation programs are written to use this value of solar radiation along with direct normal and horizontal diffuse, both of which can be estimated from the global horizontal value. If the measurement plan includes a PV system, measuring the solar radiation in the plane of the PV panels may be useful. If two pyranometers are available, both the global horizontal solar radiation and the PV plane solar radiation should be measured.

B.6 – Illuminance

Illuminance is a measurement of radiation as sensed by the human eye. Every human eye senses radiation slightly differently, but a standard spectral response curve is defined by the Commission Internationale de Eclairage (CIE, International Commission on Illumination). Photodiodes are the most common sensors for illuminance measurements. They have a nearly linear output and are very stable. The output is corrected to match the standard human eye spectral response curve.

B.7 – Relative Humidity

Several sensors are available that simplify RH measurements; however, the accuracy of the measurement is always a concern. Accuracy is typically specified only between 10% and 90% RH. Sensors usually only have a 2- to 3-year lifetime and some systems will need recalibration after sensors are replaced. It is important to measure temperature and RH at the same location so the measurements correspond. For this reason, some RH sensors are packaged with air temperature sensors. Issues involved with the location of temperature sensors, discussed in Section B.4, also apply to RH sensors.

B.8 – Flow

Building energy monitoring often requires liquid and occasionally gas flow to be measured in pipes. Flow meters can be divided into two broad categories: intrusive and nonintrusive. Intrusive meters are inserted into the flow and are based on a differential pressure measurement or a measurement based on the momentum of the fluid. They are typically very accurate and relatively inexpensive. Nonintrusive meters include ultrasonic and magnetic meters and are placed on the outside of the pipe. These meters are well suited to applications where the pressure drop of an intrusive flow meter is of critical concern, or where the fluid is dirty, such as in sewage, slurries, crude oils, chemicals, some acids, and process water. Nonintrusive meters typically cost more than intrusive meters, but they can cost less to install because systems do not need to be shut down to cut pipes for installation. Table B-1 presents a quick comparison of various flow meters (Cole-Parmer 2004).

Many installation issues must be considered when selecting a flow meter. Most types of flow meters require a long straight portion of pipe. Turbulence caused by pipe bends, valves, or other obstructions will interfere with the proper operation of the meter and result in inaccurate readings. Consult the meter literature for proper placement. Another issue is the temperature of the fluid, as some meters will not work with high-temperature fluids. Some intrusive meters may introduce an unacceptably high pressure drop in the line. To measure liquids with viscosity that is very different from water, the flow meter may need to be specially calibrated or adjusted for the different fluid properties.

Flow in ducts is usually measured with a pitot-static tube and manometer (which measures the velocity and static pressure), a thermal (hot-wire) anemometer, or a laser Doppler anemometer. The latter meter is expensive and complex, so it is generally used only in a laboratory. The flow in ducts is not uniform across a cross-section of the duct; therefore, the flow should be measured in several positions in the duct. The total flow is then found by area averaging or other more accurate methods that take into account the variations in flow. See the ASHRAE *Handbook of Fundamentals* Chapter 14 Measurement and Instruments for more details (ASHRAE 2005).

Table B–1 Flow Meter Comparisons (Cole-Parmer 2004)

Flow Meter	Fluids	Advantages	Disadvantages
Variable Area	Gases and liquids, high viscosity with calibration	Low cost, easy to read, long life	Susceptible to changes in pressure and density, must be manually read
Mass Flow Meters	Clean gases	Not susceptible to changes in pressure and density	Must be clean dry gas
Turbine	Gases and liquids, high viscosity with calibration	High accuracy, high temperature applications, small, rugged	Can become clogged, moving parts that can wear out
Differential Pressure	Clean gases and liquids	No need to recalibrate for different gases	Needs very clean fluid
Vortex	Clean gases, steam, clean liquids	No moving parts, long-term accuracy and repeatability	Not good for low fluid velocities (below 0.3 ft/s), requires long straight pipe run (10 pipe diameters before and after)
Oval Gear	Clean liquids, high viscosity with calibration	Independent of fluid viscosity, does not require straight line of pipe for installation	Can have fluid slippage with water or water like fluids
Coriolis	Clean gases and liquids, high viscosity with calibration	High accuracy even with changing temperatures and pressures	Higher cost, high pressure drop, large space needed for installation
Doppler Ultrasonic	Dirty liquids and gases	Non-intrusive, no parts to wear out, pipe sizes ½ in to 200 in, no pressure drop	Must have bubbles or particulates in liquid, lower accuracy and repeatability
Transient Time Ultrasonic	Clean liquids and gases	Non-intrusive, no parts to wear out, pipe sizes ½ in to 200 in, no pressure drop	Must have clean liquid, lower accuracy and repeatability
Magnetic Flow Meter	Conductive liquids	Very low pressure drop, insensitive to viscosity changes, good accuracy, large range of pipe sizes	Fluid must be conductive

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Appendix C – Uncertainty Analysis

C.1 – Background

Estimating uncertainty is an important step in data reduction and expression of results. This section introduces uncertainty analysis and provides an uncertainty analysis method for this procedure. The approach outlined here contains many simplifications from a rigorous uncertainty analysis. Our intent is to provide a practical approach without losing the essential uncertainty effects. This procedure is compatible with standard International and U.S. practices from the International Organization for Standardization (ISO 1995), National Institute of Standards and Technology (NIST 1994), American Society of Mechanical Engineers (ASME 1998), and the Instrument Society of America (Dieck 1997).

Uncertainty analysis in building monitoring projects is often neglected either because the practitioner knows that the uncertainty will be small, or because the practitioner does not know how to complete the uncertainty analysis and is overwhelmed by the complexities of rigorous uncertainty analysis. If the correct size instruments are used and they are installed and operated properly, the uncertainty is usually small and within the desired accuracy for building monitoring projects. Nevertheless, this does not relieve the practitioner from having to understanding error and uncertainty.

There is often confusion between *error* and *uncertainty*. *Error* is the difference between the true value, which we do not know, and the measured value; therefore, the error is unknowable. *Uncertainty* is an estimate of the limits of the error. The terms have different meanings and should not be confused. Every step in the process of making a measurement and reducing the data can introduce an error. The practitioner must be careful to recognize and minimize the sources of error to develop a reasonable estimate of the measurements' uncertainty.

Error is often described as having random and systematic components. The effects of random errors arise from unpredictable temporal or spatial variations in repeated observations of the *measurand*. All other errors are classified as systematic errors (also called *bias errors*). All errors should be minimized or adjusted for as practical by careful experimental design, sensor selection, sensor placement, calibration, data acquisition, and data reduction.

The ISO guideline divides uncertainty by the method used to determine it and not by the source. Type A evaluation of uncertainty is from statistical analysis of a series of observations, and Type B evaluation of uncertainty includes all other analysis that is not Type A. ASME (1998) and Dieck (1997) use a slightly different approach by dividing the uncertainties by the effect. Effects that cause scatter in the results are classified as random uncertainties; all others are systematic uncertainties. This procedure follows the ISO approach for classifying uncertainties, but applies the terms *random* and *systematic* to the Type A and Type B uncertainties.

Uncertainties are generally combined as the square root of the sum of the squares. The random and systematic uncertainties are treated separately, then combined to arrive at the final uncertainty. A coverage factor *k* is sometimes used to provide the desired confidence interval. For example, the following uncertainties have coverage factors of 1.7 for 90% confidence and 2 for 95% confidence, and assume adequate degrees of freedom.

$$U_{90} = 1.7\left[U_B^2 + U_A^2\right]^{1/2} \tag{C.1}$$

$$U_{95} = 2.0\left[U_B^2 + U_A^2\right]^{1/2} \tag{C.2}$$

These equations assume that (1) the uncertainties U_A and U_B have symmetric and normal distributions; (2) the uncertainties are at the standard deviation confidence level (68% coverage); and (3) the uncertainties have a large degrees of freedom (≥ 30). In this procedure, we make these assumptions unless we have specific information to the contrary. The value of the coverage factor (k = 1.7) comes from the t-distribution for 90% confidence with a degree of freedom greater than 30, as shown in Table C-1. The 90% confidence interval (sometimes stated as 90% coverage) means that 9 of 10 observations should satisfy $x = \bar{x} \pm U_{90}$. This procedure requires that uncertainties be reported at the 90% confidence level unless project requirements dictate otherwise. If the confidence levels of uncertainties from outside this procedure are not known, a knowledgeable estimate will have to be made.

Uncertainty analysis should be completed before (pretest) and after (posttest) a monitoring project. The purpose of the pretest uncertainty analysis is to determine whether the designed approach will fit within the accuracy and cost constraints of the monitoring project. The research plan may have to be altered to find the best balance between accuracy, cost, and effort. The uncertainty analysis should be repeated following the monitoring exercise with the actual sensor and measurement data to determine the uncertainty of the final result and whether the uncertainty is within the accuracy requirements. In addition, the pretest and posttest uncertainty analyses should be compared with each other and any major discrepancies corrected.

C.2 – Uncertainty Analysis Procedure

As every building energy-monitoring project is different, so is every uncertainty analysis. However, general steps should be followed, and Table C-1 provides an outline of an uncertainty analysis procedure. The procedure represents a balance between rigorous and practical approaches.

Table C-1 Uncertainty Analysis Procedure

Step	Reference
1. Define Measurement Problem • List measurements, instruments, accuracies, and equations used in analysis	
2. Identify Error Sources • List potential sources of error and estimated uncertainties	Table C-2 Section C.5
3. List Uncertainties • List uncertainties in a table format by type (random or systematic)	Sections C.3, C.4, and C.5
4. Determine Sensitivity Coefficients • Determine the sensitivity coefficients from functions used in the analysis and enter in the table	Section C.6 Equations C.6 and C.7
5. Determine the Degrees of Freedom and Coverage Factor • List degrees of freedom in the table • Determine the effective degrees of freedom • Determine the desired coverage factor	Section C.7 Equations C.10 and C.11 Table C-1
6. Combine the Uncertainties • Combine random and systematic uncertainties separately then combine and apply the appropriate coverage factor	Section C.6 Equations C.8 and C.9
7. Report the Uncertainties • Report the final result with the uncertainty and confidence interval	

C.3 – Random Uncertainty

Unpredictable variation or scatter that is apparent in repeated observations of an event under the same conditions is called *random error*. Measurements in buildings are rarely repeated under constant conditions; however, random error may result from regression analysis or be assigned to sensor calibrations.

The uncertainty approximation of the random error in a sample of n observations is estimated from the sample standard deviation as in Equation C.3. Usually we are interested in the mean value of a sample of measurements, and the random uncertainty of the mean value is estimated as the standard deviation of the mean as given by Equation C.4. The sample standard deviation is the random uncertainty of each measurement; the standard deviation of the mean is the random uncertainty of the mean of all the measurements. The degree of freedom ν is equal to n – 1.

$$S_x = \left[\sum_{i=1}^{n} (x_i - \bar{x})^2 \Big/ (n-1) \right]^{1/2} \tag{C.3}$$

$$S_{\bar{x}} = S_x \Big/ \sqrt{n} \tag{C.4}$$

Uncertainties from instrument calibration, data acquisition, and round off errors can also contribute to the random uncertainty. If the instrument calibration does not provide enough information to estimate the division between random and systematic uncertainty, this procedure assumes all uncertainty to be systematic.

Regression models are sometimes used to correlate measured energy variables with a driving force like outdoor dry-bulb temperature. The resulting function can be used to estimate energy data for periods when it was not measured. For example, the functional expression can be used to fill missing data or estimate data for periods outside the measurement period. However, the function should be used judiciously and not beyond the range of data used to determine the function.

The residual standard deviation $S_{Y/X}$ is a measure of how well the function fits the measured data and is calculated as shown in Equation C.5 and Example C.9.4. However, it is not an absolute test of "fit" and can be misleading. Higher order relationships can sometimes provide a good fit to the data but contain oscillations between data points. A visual inspection of the function and the measured data can help determine how well the function fits the data.

$$S_{Y/X} = \left[\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{(n-p)} \right]^{1/2} \tag{C.5}$$

The measured dependent variables are y_i and the function values are $\hat{y}_i$. The degrees of freedom is $\nu = (n - p)$, where n is the number of observations used to determine the functional relationship and p is the number of parameters in the function. Section C.7 provides more discussion on degrees of freedom.

C.4 – Systematic Uncertainty

Systematic uncertainties are from all error sources that are not classified as random. Estimated values of the systematic uncertainties come from experience, engineering judgment, and careful analysis of the results. Instrument drift can increase the systematic uncertainty, which can be a problem for long-term monitoring projects. All instruments should be calibrated or replaced according to the manufacturers' recommendations, or sooner if problems are suspected.

Most systematic uncertainties are assumed to have equal positive and negative magnitude and probability. Furthermore, unless more information is known, the systematic uncertainties are assumed to have a normal distribution and a 95% confidence interval (ASME 1998). If more details are known, they should be used to handle the systematic uncertainties. If the calibration history is not well known, a more conservative approach is to assume 68% coverage ($U_B = s$). If the physical characteristics of the measurement dictate that the systematic uncertainties are not symmetric about the expected value, the positive and negative uncertainties should be calculated separately.

C.5 – Uncertainty Sources

The first goal of uncertainty analysis is to reduce the possible sources of uncertainty as much as practical. Grouping the sources of potential uncertainties is a helpful, but not necessary, step in uncertainty analysis. Grouping helps identify and track uncertainty sources. Table C-2 summarizes the sources of uncertainties and how to deal with them in this procedure. All standard uncertainties, either random U_A or systematic U_B, are estimated at the level of confidence of the standard deviation. For a normal distribution, the standard deviation provides an uncertainty with a confidence interval of approximately 68% (i.e., 68% of the observations are expected to lie within $\overline{X} \pm S_x$).

Table C-2 Summary of Uncertainty Sources

Source	Type	Uncertainty	Degrees of Freedom	Comments
Repeated Observations	Random	$U_A = S_{\overline{X}}$	$\nu = n - 1$	Equations C.3 and C.4
Regression Analysis	Random	$U_A = S_{Y/X}$	$\nu = n - p$	Equation C.5
Sensor Calibration Accuracy, s	Systematic	$U_B = S/2$	$\nu > 30$	If there is confidence in the sensor and the calibration, assume (1) symmetric and normal distribution, (2) 95% coverage, and (3) large degree of freedom (>30).
Sensor Calibration Accuracy, s	Systematic	$U_B = S$	$\nu > 30$	If there is limited confidence in and information about the sensor calibration, assume (1) symmetric and normal distribution, (2) 68% coverage, and (3) large degree of freedom (>30).
Sensor Calibration Accuracy, s	Systematic and Random	Estimate U_A & U_B from S		If detailed information is known about the sensor accuracy, it can be used to estimate U_A, U_B, and ν.
Resolution and Round Off Error	Systematic	$U_B = a/\sqrt{3}$	$\nu \to \infty$	Assume (1) rectangular distribution with equal probability and (2) half width of distribution $a = (a^- + a^+)/2$.
Measurement & Analysis Methods	Systematic	Estimated	Equation C.10	Uncertainty is based on best engineering judgment and degrees of freedom is based on an assumed reliability of the estimated uncertainty.
Other				Use best engineering judgment along with other references where appropriate.

ASME (1998) and Dieck (1997) provide the following general uncertainty groups:

- *Calibration uncertainties* are from the limited precision of instruments. Instruments are calibrated to achieve a small combination of systematic uncertainty of the standard instrument and the random uncertainty of the comparison. The magnitude of this uncertainty can be obtained from the manufacturers' specifications or field calibrations. If there is not enough information to estimate the division between random and systematic uncertainty, this procedure assumes that all uncertainty is systematic. Most calibration uncertainties will be assumed to have symmetric and normal distributions and to have 95% coverage ($U_B = s/2$). If the calibration history is not well known, a more conservative approach is to assume 68% coverage ($U_B = s$).
- *Data acquisition uncertainties* include limitations in sensing and recording signals, signal conditioning, and the sensors. These uncertainties can be reduced by overall measurement system field calibrations. The data logger error may be stated as a percent of the measurement at the data logger (usually a current or voltage). There may also be a resolution error when the analog signal is rounded off because only a limited number of digits can be stored and transmitted. These uncertainties also include those introduced by manual reading and recording data. Manually read meters sometimes have low resolution and can be misread.
- *Data reduction uncertainties* come from processing raw data. Computational round off errors are usually very small and are neglected. However, errors from curve fits to measured data can be significant. Regression models are often used to relate a dependent variable to independent variables, such as energy consumption to outdoor temperature. Regression models can be used to fill in missing data or extrapolate beyond the measurement period. The simplest estimate of the modeling uncertainty is given by the residual standard deviation as shown in Equation C.5. Uncertainty should also be estimated for all data from sources that are not directly measured.
- *Uncertainties due to methods* are from the techniques in the measurement process. Examples of these uncertainties include those embedded in calculations such as constants or material properties; obtrusive disturbance of a medium by the sensors; spatial averaging of discrete points; environmental effects such as convection, conduction, and radiation; and instability and hysteresis in the sensor. Installation effects should be minimized with careful planning and field calibration of the measurement systems. Even with careful placement, they represent the largest potential uncertainties for measurement of physical phenomena such as temperatures and fluid flows. For example, consider the temperature measurement of a fluid in a pipe by inserting a thermocouple (TC) probe in a thermal well in the pipe. Probe errors will result from thermal resistance between the fluid and the TC and from conduction along the thermal well and thermal couple to the surrounding environment. Spatial errors will result from measuring the fluid temperature in one spot in the pipe and assigning this value to be the average of all the fluid in the cross section of pipe. Another spatial error that may be significant is that the sensor may be at a different location along the length of the pipe relative to the desired point of measurement.

C.6 – Combining Uncertainties

In general, uncertainties are combined as the square root of the sum of the squares. To combine uncertainties, they must be at the same level of confidence. Combining uncertainties is usually done at the standard deviation level of confidence, which is 68%. Random (Type A) and systematic (Type B) uncertainties should be summed separately until the end of the analysis.

The final result we are interested in is often derived from a function of measured and constant values such as $R = f(X_1, X_2, X_3, \ldots X_m)$. The effects of the uncertainty in each term (measured and constant) on the result are not the same. The most common approach to determine the relative effects of uncertainties on a result is by the use of a Taylor series expansion of the function. The first-order terms from the Taylor series expansion are the sensitivity coefficients. If the uncertainties are independent, the absolute θ_i and relative θ_i' sensitivity coefficients can be calculated analytically or approximated numerically as shown in Equations C.6 and C.7.

$$\theta_i = \frac{\partial R}{\partial X_i} \approx \frac{\Delta R}{\Delta X_i} \tag{C.6}$$

$$\theta_i' = \frac{X_i}{R}\frac{\partial R}{\partial X_i} \approx \frac{X_i}{R}\frac{\Delta R}{\Delta X_i} \tag{C.7}$$

The uncertainties (treating random and systematic separate) of the result R can then be combined as

$$U = \left[\sum_{i=1}^{n}\left(\theta_i U_{X_i}\right)^2\right]^{1/2} \tag{C.8}$$

Finally, the combined uncertainty is the combination of the random and systematic uncertainties

$$U_C = k\left[U_B^2 + U_A^2\right]^{1/2} \tag{C.9}$$

Where k is the coverage factor that provides appropriate confidence interval C in the final expression of uncertainty. Section C.7 and Table C-1 provide more information about the coverage factor and degrees of freedom.

Equation C.8 assumes that the systematic uncertainties are independent. If the uncertainties are correlated, the covariance term from the Taylor series expansion should be included in the uncertainty calculations. The covariance term contains the cross products of the uncertainties and the sensitivity coefficients. ASME (1998) and ISO (1995) contain more information on correlated uncertainties.

C.7 – Coverage Factor and Degrees of Freedom

Dieck (1997) defines the degrees of freedom ν as the freedom left in a data set for error or variability. For example, in the calculation of the sample standard deviation S_x, the sample mean $\bar{x}$ is calculated, and one degree of freedom is lost, therefore $\nu = (n - 1)$. In the calculation of the residual standard deviation from a regression curve fit, $\nu = (n - p)$, where n is the number of measured observations used to establish the correlation and p is the number of constants determined in the correlation.

For building monitoring projects, some systematic uncertainties and the degrees of freedom must be estimated. The degrees of freedom can be thought of as a measure of how good the estimated uncertainty is (or more precisely, the estimated variance). The degrees of freedom can be estimated from the following equation (ISO 1995).

$$\nu \approx \frac{1}{2}\left[\frac{\Delta u(x)}{u(x)}\right]^{-2} \tag{C.10}$$

The term in the brackets is the relative uncertainty of the estimated uncertainty u(x). It can be thought of as the reliability of the estimated uncertainty u(x). For example, if an estimated uncertainty u(x) of an instrument is believed to be reliable to within ±25% (or the relative uncertainty is ±25%), then $\nu \approx ½\ (0.25)^{-2} = 8$.

The degrees of freedom is used to determine the coverage factor k, which is used to determine the uncertainty band for different confidence levels. For example, if the degrees of freedom are greater than 30 and the data follow a normal distribution, the t-distribution for 95% confidence is approximately 2 and 1.7 for 90% confidence. Therefore, the data should lie within the bounds of $\bar{x} \pm 2U$ 95% of the time. The t-distribution is shown in Table C-1 for different confidence levels (ASHRAE 2002 and ISO 1993). Uncertainties calculated in this procedure should be estimated at a 90% confidence level unless requirements of the analysis call for a different level. The use of 90% confidence intervals for building energy measurements follows requirements in ASHRAE (2002) and IPMVP (2002) guidelines.

When two or more uncertainties are combined, the distribution can be approximated by the t-distribution with the effective degrees of freedom calculated by the Welch-Satterthwaite formula:

$$\nu_{eff} = \frac{\left(\sum_{i=1}^{n} S_i^2\right)^2}{\sum_{i=1}^{n} \frac{S_i^4}{\nu_i}} \tag{C.11}$$

Table C-3 t-Distribution

Degrees of Freedom	68% Confidence	80% Confidence	90% Confidence	95% Confidence
1	1.84	3.08	6.31	12.71
2	1.32	1.89	2.92	4.30
3	1.20	1.64	2.35	3.18
4	1.14	1.53	2.13	2.78
5	1.11	1.48	2.02	2.57
10	1	1.37	1.81	2.23
15	1	1.34	1.75	2.13
20	1	1.33	1.73	2.09
25	1	1.32	1.71	2.06
≥ 30	1	1.3	1.7	2.0
∞	1	1.28	1.65	1.96

C.8 – Definition of Terms

Combined Uncertainty – (U_c) Combination of all uncertainties, usually by the positive square root of the sum of the squares at confidence interval c.

Covariance – A measure of the dependence of two random variables.

Coverage Factor – (k) multiplier used with the *standard uncertainty* to expand the uncertainty for the desired confidence. For example, the standard deviation is multiplied by a coverage factor of 2 for 95% confidence (or coverage), assuming that the degree of freedom is ≥ 30. The coverage factor is typically based on the t-distribution (Table C–1).

Error – The difference between the true value, which is not known, and the measured value.

Measurand – The quantity being measured.

Random Error – Error from unpredictable sources that are apparent in repeated observations.

Random (Type A) Uncertainty – (U_A) Uncertainty obtained from a statistical evaluation of a series of observations that form an observed probability density function.

Residual Standard Deviation – ($S_{Y/X}$) = An estimate of the scatter of data about a curve fit through the data. It is analogous to the standard deviation for the scatter of data about a mean.

Standard Deviation – (S_x) A measure of the scatter of data about the mean equal to the positive square root of the variance. For a normal probability distribution and an infinite number of observations, approximately 68% of the observations will be contained in the interval $\overline{x} \pm S_x$. It is taken as the sample standard deviation (n-1 denominator) and not the population standard deviation (n denominator).

Standard Uncertainty (U) – Uncertainty at the standard deviation level of confidence, which is 68%.

Systematic Error – Error effects that are not attributed to random error. Systematic errors should be minimized through proper calibration and experimental design.

Systematic (Type B) Uncertainty – (U_B) Uncertainty estimated by means other than statistical. This uncertainty is based on an assumed probability density function (e.g., normal, rectangular, or triangular).

Uncertainty – An estimation of the bounds of the error.

Variance – (S_x^2) A measure of dispersion equal to the sum of the square of the difference between the measurements and the mean divided by one less than the number of measurements.

C.9 – Example Uncertainty Calculations

C.9.1 – Outdoor air dry-bulb temperature uncertainty

Estimate the uncertainty in the measurement of the outdoor air dry-bulb temperature by a type-T shielded TC. The TC is connected to a data logger that contains a built-in thermistor reference temperature and calculates the temperature from the measured voltages. The temperature sensors are scanned every 15 s and the average value is recorded every 15 min.

The significant error sources are sensor error, reference junction temperature sensor error, data acquisition error, and environmental errors. Uncertainties are assumed to be systematic with normal distributions, have 95% coverage (i.e., $U_B = U_{95}/2$), and have a large degree of freedom (≥ 30), unless otherwise noted.

- TC sensor uncertainty: Assume that the reference temperature junction is maintained at 20°C and the minimum T_{db} is –20°C for a maximum temperature differential of –40°C. The maximum error limits established by ANSI for Type-T TCs are ±1.0°C from –100°C to 100°C or 1.5%, whichever is larger. However, practical experience has shown that this is extremely conservative for the midrange. A more reasonable estimation is to use 1.5% x 40°C = ±0.6°C. Therefore, $U_{B,I}$ = ±0.6°C/2 = ±0.3°C.
- Reference junction temperature uncertainty = ±0.2°C (from data logger manufacturer). Therefore, U_B = ±0.2°C/2 = ±0.1°C.
- TC polynomial voltage temperature conversion uncertainty = ±0.001°C (data logger manufacturer). Therefore, U_B = ±0.001°C/2 = ±0.0005°C.
- Reference junction temperature to voltage conversion uncertainty = ±0.001°C (data logger manufacturer). Therefore, U_B = ±0.001°C/2 = ±0.0005°C.
- Data acquisition voltage measurement uncertainty = ±0.1% full scale reading (FSR) = ±0.0025 mV for ±2.5 mV range, which is ±0.06°C at 45°C (from data logger manufacturer)
- Data acquisition resolution uncertainty = 0.00033 mV for the ±2.5 mV range. This is much smaller than the other uncertainties and is neglected.
- Environmental uncertainty is estimated from experience to be ±0.5°C at 95% confidence with an estimated reliability of 25%. The degrees of freedom from Equation C.10 is $\nu = 8$; therefore, the t-statistic for 95% is 2.3 and U_B = ±0.5°C/2.3 = 0.22. The uncertainty is mainly due to radiation to the surroundings and convective thermal resistance around the TC.

Assuming that the uncertainties are uncorrelated, the maximum expected uncertainty in taking a single measurement is calculated in Table C-4. The effective degrees of freedom is calculated from Equation C.11 to be 39 and the coverage factor for 90% confidence is 1.7.

Table C-4 Uncertainty Analysis for a TC

Uncertainty Source	Units	Standard Systematic Uncertainty U_B	Standard Random Uncertainty U_A	Degrees of Freedom	Sensitivity Coefficient
TC Limits of Error	°C	0.3	0.0	30	1
Ref. Junction	°C	0.1	0.0	30	1
TC Voltage Conversion	°C	0.0005	0.0	30	1
Ref. Junction conversion	°C	0.0005	0.0	30	1
TC Voltage Measurement	°C	0.03	0.0	30	1
Environmental	°C	0.22	0.0	8	1
			Effective degrees of freedom =	39	

Uncertainty	Units	Standard Systematic Uncertainty $\sqrt{\sum(\theta U_B)_i^2}$	Standard Random Uncertainty $\sqrt{\sum(\theta U_A)_i^2}$	Combined Uncertainty U_{90} $k\sqrt{\sum(U_B)^2+\sum(U_A)^2}$
Thermocouple	°C	0.39	0.0	0.66

The uncertainty is therefore $U_{90} = \pm 0.7$°C with 41 degrees of freedom. Over the course of a long-term monitoring project, most of the temperature measurements would be within 20°C of the reference junction temperature, which would reduce the TC uncertainty to U_{95} ±0.3°C and the overall uncertainty, $U_{90} = \pm 0.5$°C.

C.9.2 – Electrical energy measurement uncertainty

Calculate the uncertainty in electrical energy measurements made on a 480 VAC (phase-to-phase) three-phase circuit with 100-amp current transformers (CTs) on each phase and a watt-hour meter (WHM). The CTs have a stated accuracy of ±1% of the reading between 10% and 130% of rating, and the accuracy of the WHM is ±0.45% of the reading ±0.05% of full scale. The WHM output pulses with a full-scale frequency of 4 Hz and is connected to a pulse counter with a sampling frequency of 500 Hz. A data logger scans the pulse counter every 15 s. The WHM calculates the energy by the following equation

$$E = \frac{nCTs \times VAC \times CTamps \times Pulses}{FSHz \times 3{,}600}$$

where E is the energy in watt-hours, nCTs is the number of CTs, VAC is the phase to ground voltage (nominally 277 V), CTamps is the average of the current passing through the nCTs, pulses is the number of pulses output, and FSHz is the full scale pulse frequency (4 Hz). The energy per pulse at full scale with three 100 amp CTs is 5.771 Wh/pulse.

The significant uncertainties are accuracies of the CTs and WHM. Errors associated with counting the pulses are small and are neglected. Errors in sensing the line voltage are assumed to be embedded in the accuracy of the WHM. The WHM uncertainty at full scale per pulse is calculated as the energy per pulse at full scale times the accuracy at full scale.

$$U_{WHM,95} = \pm\frac{3\times 277\times 100\times 1}{4\times 3{,}600}\times 0.50\% = \pm 0.029\ \mathrm{Wh/pulse}$$

The CT uncertainty is stated as a percentage of the current, and the sensitivity coefficient is calculated from Equation C.8.

$$U_{CT,95} = 100\times 0.01 = 1\ \mathrm{A}$$

$$\theta_{CT} = \frac{\partial E}{\partial CTamps} = \frac{3\times 277\times 1}{4\times 3{,}600} = 0.0577\ \mathrm{Wh/pulse/A}$$

Both uncertainties are assumed to be systematic with normal distributions at 95% confidence and large degrees of freedom. Therefore, the standard uncertainty U_B is found by dividing the uncertainties by a coverage factor of 2. The coverage factor to have 90% confidence in the final result with $\nu \geq 30$ is 1.7. The absolute and relative uncertainties are calculated in Table C-5.

Table C-5 Uncertainties for Electrical Energy Measurements

Uncertainty Source	Units	Standard Systematic Uncertainty U_B	Standard Random Uncertainty U_A	Degrees of Freedom	Sensitivity Coefficient
WHM (full scale 100 A)	Wh/pulse	0.014	0.0	30	1
CT (full scale 100 A)	A	0.5	0.0	30	0.0577
WHM (half scale 50 A)	Wh/pulse	0.008	0.0	30	1
CT (half scale 50 A)	A	0.25	0.0	30	0.0577
WHM (25 A)	Wh/pulse	0.0005	0.0	30	1
CT (25 A)	A	0.125	0.0	30	0.0577

Uncertainty	Units	Standard Systematic Uncertainty $\sqrt{\sum(\theta U_B)_i^2}$	Standard Random Uncertainty $\sqrt{\sum(\theta U_A)_i^2}$	Combined Uncertainty U_{90} $1.7\sqrt{\sum(U_B)^2+\sum(U_A)^2}$
Full scale 100 A	Wh/pulse	0.0323	0.0	0.055
Half scale 50 A	Wh/pulse	0.0165	0.0	0.028
Quarter scale 125 A	Wh/pulse	0.0086	0.0	0.015
Full scale 100 A	%	0.56%	0.0	0.95%
Half scale 50 A	%	0.57%	0.0	0.97%
Quarter scale 125 A	%	0.60%	0.0	1.01%

The full-scale uncertainty is $U_{90} = \pm 1\%$ with 30 degrees of freedom, and the half-scale uncertainty is $U_{90} = \pm 1\%$ with 30 degrees of freedom. The relative uncertainties apply to circuits using different sized CTs assuming the same WHM, number of CTs, and relative sensor accuracies.

This type of electrical meter would most likely be used to record 15-min or hourly total energy use, which then may also be condensed to daily, monthly, or yearly energy use. The uncertainty for the total energy measurement could be estimated in two ways: first by applying the relative uncertainties calculated above to the total energy, and second by combining the uncertainty per pulse for all the pulses in the total energy. For example, assume the energy total with an average of 50% power over 1 h is 24 kWh, which is 4,159 pulses. If we assume the uncertainty in the total energy is 1%, $U_{90} = \pm 240$ Wh. By comparison, assuming the uncertainty per pulse is $U_{90} = \pm 0.034$ Wh, the uncertainty in the total is U_{90} =

$\pm[4,159(0.028)^2]^{1/2} = \pm 1.8$ Wh. The first method is more conservative and is recommended in this procedure.

C.9.3 – Building energy use intensity uncertainty

Estimate the uncertainty in the calculation of the annual site **Building Energy Use Intensity** (**BEUI**) of a building. The building electricity use is determined from a monitoring system similar to that used in Example C.9.2 and the gas use is from the utility bill. It is a two-story building with the gross interior floor area of 28,800 ft^2 as determined from the building drawings. The annual electricity use is 745.8×10^6 Btu and the annual gas use is 497.2×10^6 Btu.

We assume that the building dimensions are measured with an accuracy of ±1 ft, and that this is a systematic uncertainty with a symmetric and normal probability distribution and 95% coverage. The uncertainty in the electricity total is assumed to be $U_{68} = \pm 0.5\%$ as determined in Example C.9.2 assuming an average of 50% power. The uncertainty in the gas measurements is based on at least three factors. The gas is billed on an energy content basis, which is determined by measuring the gas volume and multiplying by an energy multiplier. The energy multiplier is calculated monthly and depends on the energy content of the gas and the average outdoor air temperature. The accuracy of the gas meter is specified to be ±2%, which is typical for utility gas metering. This value is assumed to be a systematic uncertainty with a normal probability distribution and 95% coverage and 30 degrees of freedom. The uncertainty in the energy multiplier is assumed to be ±2% with 95% coverage, 30 degrees of freedom, and all systematic uncertainties. Finally, an uncertainty is associated with the difference in the energy multiplier and the actual energy content of the delivered gas. This uncertainty is estimated from the variation in the monthly values of the energy multiplier with temperature compensation term removed over a 3-yr period (n = 36). The uncertainty is estimated from the relative standard deviation of the monthly energy multiplier, which is s = 0.8%. The total uncertainty for the gas meter is $U_B = ((2/2)^2 + (2/2)^2)^{1/2} = 1.41\%$ and $U_A = 0.8\%$.

Building Area Uncertainty

The building dimensions for each floor are length = 160 ±1 ft and width = 90 ±1 ft. The area is calculated as A = 2 x L x W (see Table C-6).

Table C-6 Absolute Uncertainty for Building Area

Uncertainty Source	Units	Standard Systematic Uncertainty U_B	Standard Random Uncertainty U_A	Absolute Sensitivity θ_i	Combined Uncertainty U_{90} $1.7\sqrt{\sum(\theta_i U_{Bi})^2 + \sum(\theta_i U_{Ai})^2}$
Length	ft	0.5	0	2 x W = 180	
Width	ft	0.5	0	2 x L = 320	
Total	ft^2				312 ≈ 1%

Building Energy Use Intensity Uncertainty

The **BEUI** is calculated from **BUEI** = $(E_{elec} + E_{gas})/A$ (see Table C-7).

Table C-7 Absolute Uncertainty for BEUI

Uncertainty Source	Unit	Nom. Value	Standard Systematic Uncertainty U_B	Standard Random Uncertainty U_A	Absolute Sensitivity θ_i	Combined Uncertainty U_{90} $1.7\sqrt{\sum(\theta_i U_{Bi})^2 + \sum(\theta_i U_{Ai})^2}$
Area	ft^2	28,800	273	0	$-E/A^2$ = -1.499E-03	
Electric Energy	kBtu	745,800	3,729	0	1/A = 3.4722E-05	
Gas Energy	kBtu	497,200	7,011	3,978	1/A = 3.4722E-05	
BEUI	kBtu/ ft^2	43				0.9

Therefore, the **BEUI** = 43 ±0.9 kBtu/ft^2 (90% coverage). More than half of this uncertainty comes from the area measurement.

C.9.4 – Uncertainty of estimated data

In an all-electric office building, the major end uses (heating, ventilating, and air-conditioning [HVAC], lights, and plug loads) are submetered every 15 min for 1 month with the same type of electrical meter system as that used in Example C.9.2. The on-site weather conditions (dry-bulb temperature, RH, and global horizontal solar radiation) are also measured on the same time interval. The electrical monitoring system was down for 9 days in the middle of a month; however, the weather data were recorded for the entire month. The building operating schedule is consistent for weekdays and weekends according to the light and plug load energy use. The HVAC controls did not change during this period. The weekday and weekend control settings for the HVAC systems are very different, so they should be treated separately. The measured dry-bulb temperature and HVAC energy is shown in Table C-10. The missing measured data (shown shaded) are filled with the linear regression formula.

Estimate the weekday HVAC energy consumption for the month by filling in the missing data.

The missing data can be estimated by multiplying the average of the measured daily energy use by the number of missing days, or from a linear regression between the daily HVAC energy use and the daily outdoor dry-bulb temperature. Both methods will be completed here for comparison. There are 23 weekdays during the month and 16 weekdays of good data; therefore, there are 7 days of missing energy data. The total energy for the 16 days of measured data is 6,598 kWh.

Method #1 – Average daily energy use

From the weekday measured energy data, the average daily HVAC energy is E_{avg} = 412.4 kWh with a standard deviation of 35.0 kWh (Equation C.3). The average value was used to fill in the days of missing data to give a 7 day total of 2,887 kWh and a monthly weekday (23 day) total of 9,485 kWh. The random uncertainty for the sum of the 7 days is $U_{A-68} = [7 \text{ x } (35)^2]^{1/2}$ = 92.6 kWh. The systematic uncertainty is taken from Example C.9.2 to be U_{B-68} = ±0.5% assuming an average of 50% power for the whole 23 days. Assuming the degrees of freedom is 30 for the systematic uncertainty and 15 for the random uncertainty, the effective degrees of freedom from Equation C.11 is 23. The coverage factor for 90% confidence is 1.71.

Table C-8 Uncertainty for Filling Data with Averaging

Uncertainty Source	Units	Standard Systematic Uncertainty U_B	Standard Random Uncertainty U_A	Degrees of Freedom	Sensitivity Coefficient
Regression Analysis	kWh	0	92.6	15	1
WHM	kWh	46.3	0.0	30	1
			Effective degrees of freedom =	23	

Uncertainty	Units	Standard Systematic Uncertainty $\sqrt{\sum(\theta U_B)_i^2}$	Standard Random Uncertainty $\sqrt{\sum(\theta U_A)_i^2}$	Combined Uncertainty U_{90} $1.71\sqrt{\sum(U_B)^2+\sum(U_A)^2}$
Monthly Total	kWh	46.3	92.6	177

The total weekday HVAC energy use for the month is estimated by the averaging method to be

$E = 9{,}485 \pm 177$ kWh at 90% confidence

Method #2 – Linear regression of daily HVAC energy and outdoor temperature

The linear regression of the daily HVAC energy use with daily average outdoor temperature produces the function $E = 5.357T_{db} + 27.23$ as shown in Figure C-1, which gives an estimated total for the 7 missing days of E = 2,790 kWh. The residual standard deviation for estimating 1 day of energy use is calculated from Equation C.5 to be 24.2 kWh. The random uncertainty for the sum of the 7 days is $U_{A\text{-}68} = [7 \times (24.2)^2]^{1/2} = 64.1$ kWh. The systematic uncertainty is taken from Example C.9.2 to be $U_{B\text{-}68} = \pm 0.5\%$ assuming an average of 50% power for all 23 days. There are 14 degrees of freedom (16 days of data minus 2 parameters in the linear regression formula) for the random uncertainty and 30 for the systematic uncertainty. Before applying the linear regression formula, the average daily temperature for the days of missing energy data is verified to be within the range of average daily temperatures for the days with measured energy data. One day is 1.5°F cooler than the lowest daily temperature in the measured data set, and one day is 1.2°F warmer than the highest daily temperature in the measured data set. These two days are only slightly outside the range of data used in the regression, and the building systems should have the same operating characteristics at these temperatures. Therefore, the error should be within the uncertainty bounds.

Table C-9 Uncertainty for Filling Data with Regression Analysis

Uncertainty Source	Units	Standard Systematic Uncertainty U_B	Standard Random Uncertainty U_A	Degrees of Freedom	Sensitivity Coefficient
Regression Analysis	kWh	0	64.0	14	1
WHM	kWh	46.9	0.0	30	1
		Effective degrees of freedom =		29	

Uncertainty	Units	Standard Systematic Uncertainty $\sqrt{\sum(\theta U_B)_i^2}$	Standard Random Uncertainty $\sqrt{\sum(\theta U_A)_i^2}$	Combined Uncertainty U_{90} $1.7\sqrt{\sum(U_B)^2+\sum(U_A)^2}$
Monthly Total	kWh	46.9	64.0	135

E_{reg} = 9,405 ±135 kWh at 90% confidence

The uncertainty from the regression method is smaller than from the averaging method, which is expected because the averaging method does not account for weather variations. The difference in total energy between the two methods is 80 kWh, which is within the uncertainty bounds of the both methods.

Table C-10 Dry-Bulb Temperature and HVAC Energy (Filled Data Are Shaded)

T (°F)	E (kWh)		T (°F)	E (kWh)
75.2	462.5		76.1	422.5
75.4	430.3		75.2	411.0
77.0	438.5		73.3	451.8
77.9	433.3		69.7	416.5
72.0	465.0		71.0	373.5
63.7	369.7		75.1	401.5
60.5	352.0		70.9	397.0
62.8	364.8		67.6	403.3
68.2	393.5		69.9	388.8
73.9	424.0		62.0	356.3
75.7	433.9		62.0	346.5
79.2	452.6			

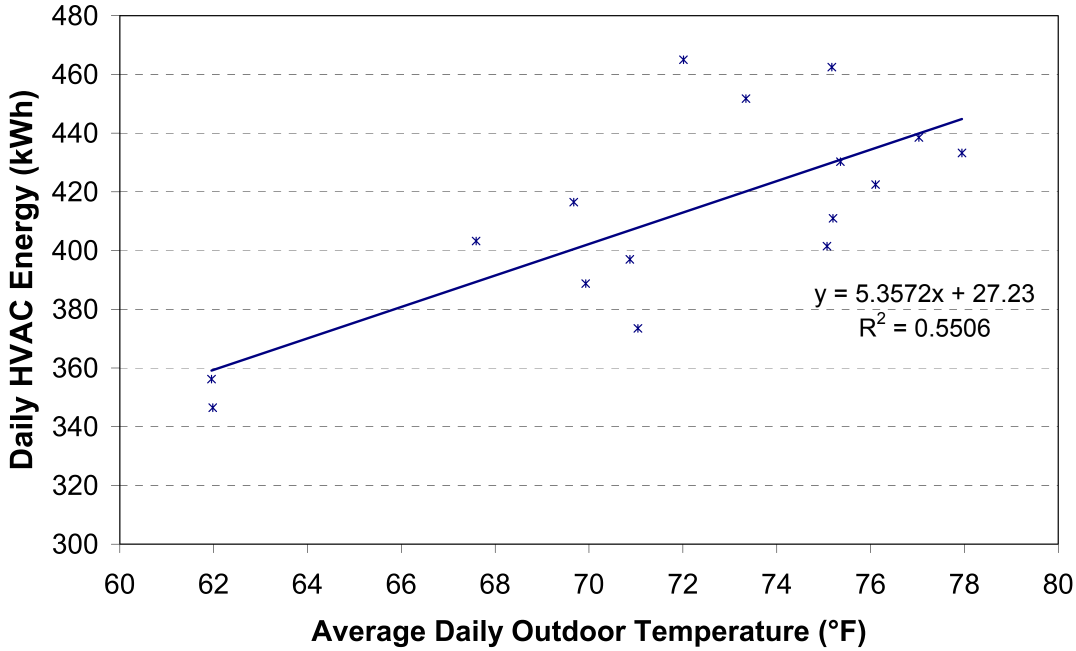

Figure C-1 Linear regression of daily HVAC energy and average daily outdoor temperature

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Appendix D – Demand and Load Factor Performance Metrics

Peak electrical demand and load factor performance metrics are used by building energy managers to determine how well they are balancing the building energy use and by utilities to determine how much extra capacity they need to meet all the electrical loads of buildings. The peak electrical demand is typically defined as the highest average power over any 15-minute window in a month. The load factor is a dimensionless number and is the ratio of the average electrical energy and the peak electrical demand. Buildings often have load factors around 0.5, which means that the peak demand is two times higher than the average power. Utilities charge for peak demand in order to support the extra capacity needed in the system. Demand charges can be more than half the electric utility bill; therefore, it is in the best interest of the building owner to reduce peak demands.

Energy efficient buildings strive to lower the energy consumption; however, they often do not reduce the demand by the same amount. If the energy use is reduced more than the peak demand, the load factor goes down. This means that the utilities will have to supply less energy, but there is no reduction in capacity requirements. Therefore, the utilities still have to maintain the same generation, transmission and distribution capacities, which is very expensive. Keeping power plants in spinning reserve waiting for higher demands requires energy, so even though a building may reduce site energy consumption, the source energy consumption may not be reduced by the same amount. Even buildings with on-site electricity generation from PV systems rarely reduce demand by more than a few percent. Energy efficient buildings should manage peak demand with demand limiting controls and possibly on-site energy storage.

Buildings that employ energy efficiency and PV systems to approach zero net energy can export electricity to the grid when the PV systems produce more than is used in the buildings. If the building exports more energy than it uses over a month or a year, then the load factor can be negative depending on how it is defined. A negative load factor has a very different meaning from a utility point of view. It tells them that the building exported electricity, but it does not tell them the capacity they need to have to meet the building loads.

We have defined several demand and load factor metrics to tell different parts of the story. Table D-1 lists the performance metrics with a description. The **Net Facility Load Factor** can become negative for buildings that export electricity.

Figure D-1 shows actual measured monthly peak demand for an all electric building with a small PV system that meets approximately 8% of the building electricity use. This figure shows the **Total Facility Electrical Demand**, the **Net Facility Electrical Demand**, and the **Net Facility Electrical Demand** with a PV system large enough to make the building a net zero energy building (ZEB). The electrical demand for this building usually occurs in the morning when the PV system is not producing energy; therefore, the peak demand is not affected by the PV system.

Figure D-2 shows the different load factors for this same building. Notice that the **Net Facility Load Factor** becomes negative for the ZEB building. The monthly value of **Net Facility Load Factor** is negative for any month that the building is a net exporter of electricity, and the annual value is zero by definition for a net ZEB. The **Effective Facility Load Factor** is a ratio of the average electricity into the building and the peak demand.

Table D-1 Peak Electrical Demand and Load Factor Performance Metrics

Performance Metric	Description
Total Facility Electrical Demand	Peak electrical demand of the facility with no electricity generation from on-site systems. This metric is an indicator of how well the facility manages the electrical loads.
Net Facility Electrical Demand	Peak electrical demand of the facility as seen by the electric utility. This metric includes all electricity generated on site. This metric is an indicator of the impact of the building on the utility grid. This is the same as the Total Facility Electrical Demand if there is no on-site energy generation.
Building Electrical Demand	Peak electrical demand of the building with no electricity generation from on-site systems or co-generation systems. This metric is an indicator of how well the building manages the electrical loads. This is the same as the **Total Facility Electrical Demand** if there are no process loads or outdoor energy use.
Net Facility Load Factor	Ratio of the hourly average **Net Facility Electrical Energy Use** and the **Net Facility Electrical Demand**. This metric includes energy exported from the site and can be come negative. A negative load factor has a different meaning and should be interpreted carefully.
Effective Facility Load Factor	Ratio of the hourly average positive **Net Facility Electrical Energy Use** and the **Net Facility Electrical Demand**. This metric only includes the energy into the building and does not include energy exported from the site. This metric does provide an indication of the impact of the building on the utility. This metric is the same as the **Net Facility Load Factor** for buildings that do not export electricity and is the same as the **Total Facility Load Factor** for buildings that do not have on-site electricity generation. This metric becomes zero or undefined if the facility does not draw any energy from the grid.
Total Facility Load Factor	Ratio of the hourly average **Total Facility Electrical Energy Use** and the **Total Facility Electrical Demand**.
Building Load Factor	Ratio of the hourly average **Building Electrical Energy Use** and the **Building Electrical Demand**. This metric is the same as the **Total Facility Load Factor** for buildings that do not have process or outdoor loads.
Building Electrical Demand Intensity	Ratio of the **Building Electrical Demand** and the **Functional Area** (**Gross Interior Floor Area**). Normalizing by the area allows this metric to be used to compare the performance of different buildings with each other.

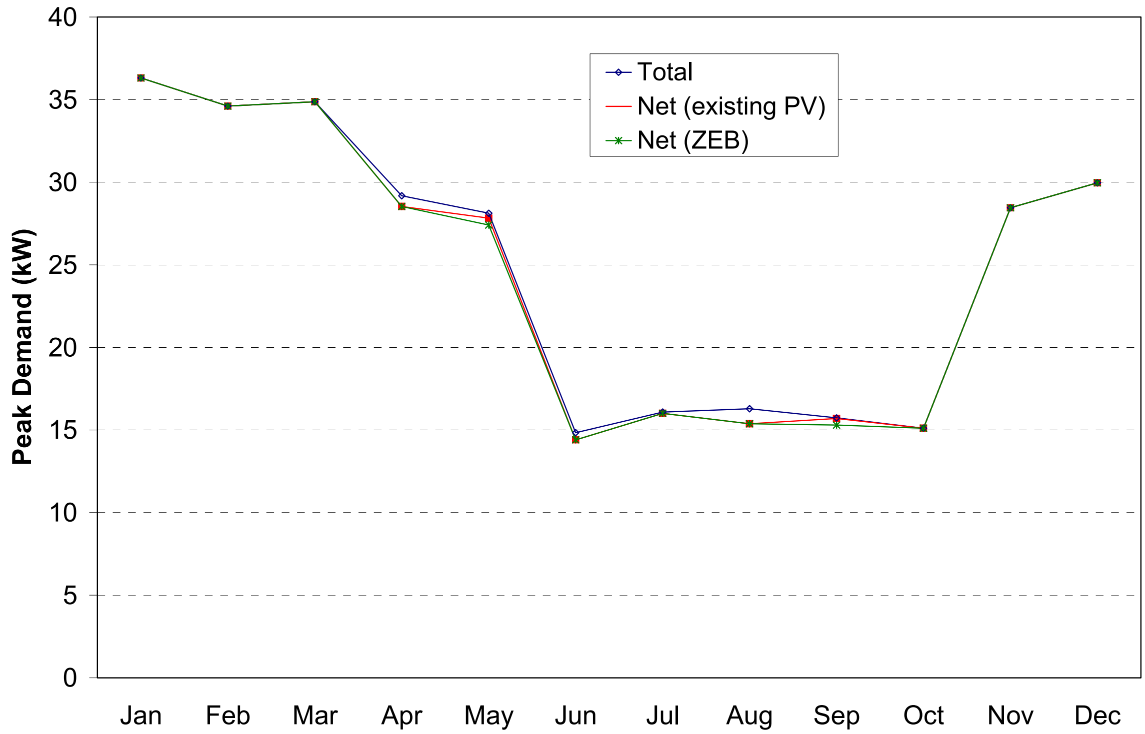

Figure D-1 **Peak electrical demand of a building with no PV, existing PV, and enough PV to make the building a net zero energy building**

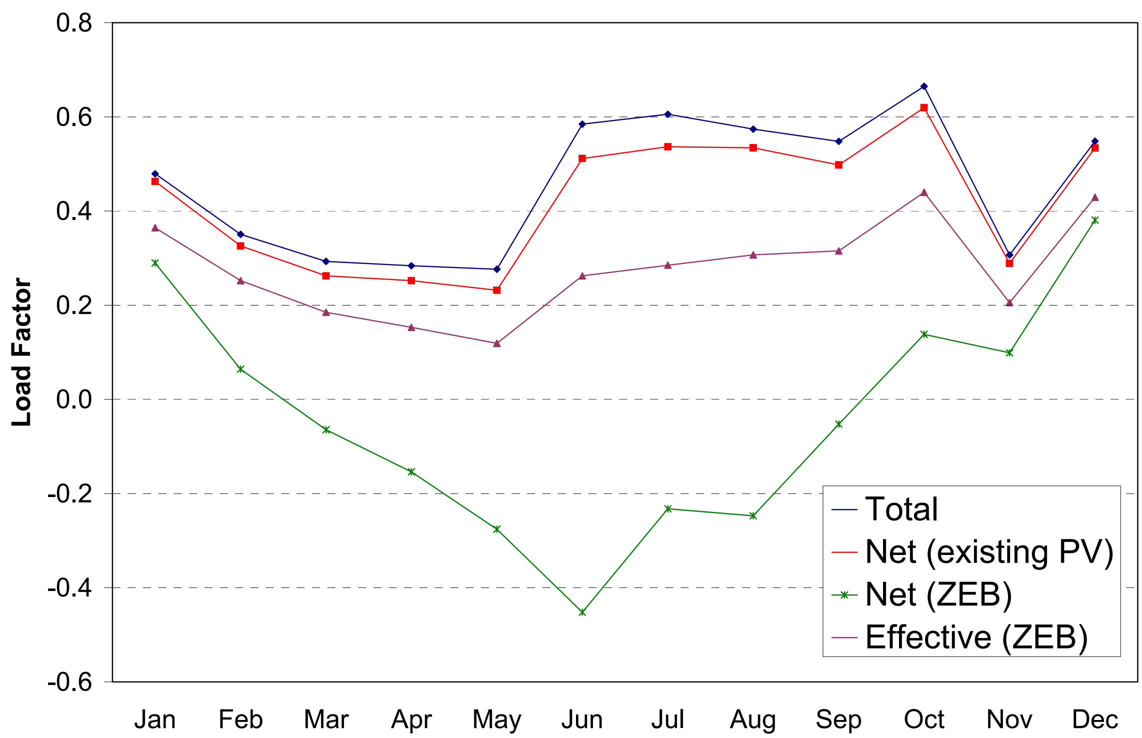

Figure D-2 **Load factors for a building with no PV, existing PV, and enough PV to make the building a net zero energy building**

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
October 2005	Technical report	2004-2005

4. TITLE AND SUBTITLE
Procedure for Measuring and Reporting Commercial Building Energy Performance

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
D. Barley, M. Deru, S. Pless, and P. Torcellini

5d. PROJECT NUMBER
NREL/TP-550-38601

5e. TASK NUMBER
BEC3.3003

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-550-38601

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This procedure is intended to provide a standard method for measuring and characterizing the energy performance of commercial buildings. The procedure determines the energy consumption, electrical energy demand, and on-site energy production in existing commercial buildings of all types. The performance metrics determined here may be compared against benchmarks to evaluate performance and verify that performance targets have been achieved.

15. SUBJECT TERMS
performance metrics; building energy analysis; building energy performance; measurement and characterization; energy consumption; commercial buildings

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		
					19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18