

Strategies for Energy Benchmarking In Cleanrooms and Laboratory-Type Facilities

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ABSTRACT

Buildings with cleanrooms and laboratories are growing in terms of total floor area and energy intensity. This building type is common in institutions such as universities and in many industries such as microelectronics and biotechnology. These buildings, with high ventilation rates and special environmental considerations, consume from 4 to 100 times more energy per square foot than conventional commercial buildings. Owners and operators of such facilities know they are expensive to operate, but have little way of knowing if their facilities are efficient or inefficient. A simple comparison of energy consumption per square foot is of little value. A growing interest in benchmarking is also fueled by:

- A new US Executive Order removing the exemption of federal laboratories from energy efficiency goals, setting a 25% savings target, and calling for baseline guidance to measure progress.
- A new US EPA and US DOE initiative, Laboratories for the 21st Century, establishing voluntary performance goals and criteria for recognition.
- A new PG&E market transformation program to improve energy efficiency in high tech facilities, including a cleanroom energy use benchmarking project.

This paper identifies the unique issues associated with benchmarking energy use in high-tech facilities. Specific options discussed include statistical comparisons, point-based rating systems, model-based techniques, and hierarchical end-use and performance-metrics evaluations.

Introduction

Project Objectives

The purpose of this paper is to provide an overview of strategies for benchmarking energy use in buildings with cleanrooms and laboratories. These buildings are four to one hundred times more energy-intensive than typical office buildings. There are three drivers motivating the development of cleanroom and laboratory benchmarking strategies:

- A new US Executive Order (13123) removing the exemption of federal laboratories from energy efficiency goals, setting a 25% savings target, and calling for baseline guidance to measure progress.
- A new US EPA and US DOE initiative, Laboratories for the 21st Century, establishing voluntary performance goals and criteria for recognition.
- A new PG&E market transformation program to improve energy efficiency in high tech facilities, including a cleanroom energy use benchmarking project.

Each of these is further described in the Discussion section of this paper. We use the term "energy performance benchmarking" to refer to the comparison of whole building, system, or

component energy use and energy performance, to a comparable data set. Data included in an energy benchmarking activity can include energy use, energy costs, peak demand, time-of-use data, building characteristics, and non-energy performance features. Comparison data sets can include:

- similar buildings
- historical energy use for the given building (usually referred to as "baselining")
- a set of similar systems or components.

The most significant challenge in energy performance benchmarking is to ensure that the data are being compared in the most meaningful way possible. There are so many confounding factors in such comparisons that one could easily misinterpret comparison data and draw inappropriate conclusions. Also, use of production metrics, such as kW/cm² of silicon produced, could mask inefficient systems or components. Review of the existing publicly available energy data for clean rooms and laboratory-type buildings reveals a paucity of sources of information, such as end-use profiles and load-shape analysis, that are fundamental to understanding the patterns of energy use in such facilities. One current obstacle is the deficiency of clear protocols, survey strategies, metrics, and tools necessary for benchmarking of energy performance.

We begin with an overview of the concept of benchmarking as a "best-practice" process-improvement strategy. We then discuss the unique energy issues associated with cleanrooms and laboratory-type buildings. This discussion is followed by a presentation of four types of strategies used for benchmarking: 1) statistical comparisons, 2) point-based rating systems, 3) model-based techniques, and 4) hierarchical end use and performance metrics evaluations. Finally, we present a discussion of how these approaches relate to the projects and drivers for cleanroom and laboratory building energy benchmarking.

Benchmarking for Process Improvement

This section provides an overview of benchmarking principles as they relate to business practices and continuous process improvement. Such concepts are useful to help define how industrial facilities' managers might utilize energy benchmarking to improve processes that influence their facilities' energy use.

A benchmark is *a marked point of known or assumed evaluation* (Random House, 1980). There is a great explosion in interest and activities associated with benchmarking. The activity itself is facilitated by information technology including the Internet, plus data collection, management, archival, and visualization tools. The most common use of the term benchmarking is the process of measuring various facility, industrial, or general business processes in order to manage costs, productivity, or services. A single query on any of today's web search engines using the term "benchmarking" provides over 20,000 to 50,000 matches.

Benchmarking is strongly related to Total Quality Management (TQM), in which one defines metrics and methods to measure business attributes. Benchmarking and TQM activities consist of comparing quantitative attributes for one's own organization to both their own historic data and to other organizations to be "benchmarked against" over time. This allows business managers to search for cost-cutting or productivity-enhancing strategies that can be "measured" and evaluated. Benchmarks are measurements to gauge the performance of a function, operation, or business, relative to others (Bogan and English, 1994). By

contrast, benchmarking is the actual process of investigation and discovery that emphasizes operating procedures as the things of greatest interest and value. Best practices benchmarking is the process of seeking out and studying the best internal and external practices that produce superior performance. One measures this performance through various financial and non-financial indicators.

Figure 1 shows a chronological sequence for benchmarking as a learning process to analyze workflows and performance measures (McNair and Leibfried, 1992). Core issues are the selection of key processes and metrics to be benchmarked. Internal data collection includes developing a process flow map and a benchmark questionnaire. Special attention is needed to ensure that data definitions are as tight and consistent as possible. The external data collection step consists of compiling data for benchmark targets. The analysis phase consists of comparing the benchmark data and identifying opportunities. The final step is to implement changes and evaluate resultant improvements to close identified performance gaps.

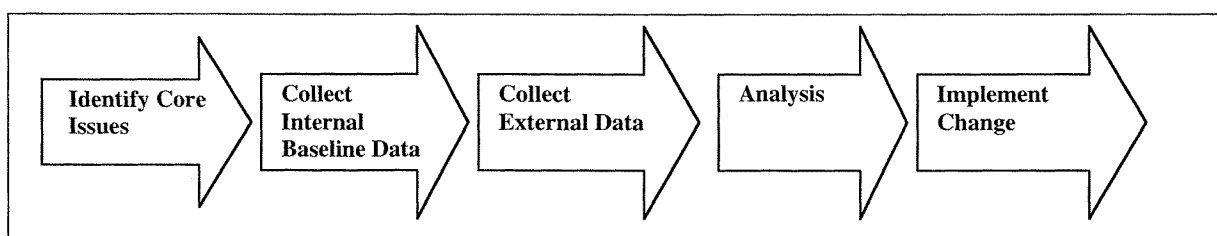


Figure 1. A Framework for Benchmarking

Benchmarking Cleanrooms and Laboratory-Type Buildings

Many of the principles surrounding the concepts of benchmarking for best practices and continuous improvement are relevant to energy performance benchmarking in buildings. Examples of organizations that have been active in benchmarking buildings include the International Facility Management Association (www.ifma.com), The Building Owners and Managers Associations (www.boma.org), and Facilities Management Datacom (www.fmdata.com). Government agencies such as the US DOE and US EPA are also involved in benchmarking, as further described below. EPA introduces the concept of benchmarking of building energy performance as follows (www.epa.gov/buildings/label/):

"The process of comparison against a standard or average is often referred to as benchmarking. Benchmarking can help you determine how well a building is performing in terms of energy efficiency; set targets for improved performance; facilitate a more accurate assessment of property value; and in some cases gain recognition for exemplary achievement."

The primary reason to develop methods for benchmarking energy performance in cleanrooms and laboratory-type buildings is to facilitate the identification of best practices related to energy efficiency strategies. Because they are energy-intensive, significant cost-effective opportunities exist for savings. As much as a 50% reduction in energy intensity can be achieved, primarily through improved integrated design, commissioning, and operations (Mills et al. 1996). Characteristics of high tech buildings that are coupled with high energy use include high ventilation rates for make-up or recirculated air, strict temperature and humidity requirements, filtration requirements, and the use of fume hoods.

Cleanrooms and laboratories can be found in a variety of industries and institutions using different building types. Cleanrooms are most often used in manufacturing. They are found in the production of semiconductors and other electronic components, and they are also common in the pharmaceutical and biotechnology industries. There are a variety of cleanroom cleanliness classes. The classification is based upon the number of particles greater than, or equal to, a certain size-per-unit volume of air. Energy intensity generally increases with the level of cleanliness. Figure 2 shows a typical energy use intensity (EUI) for heating, ventilation, and air conditioning (not total EUI) for several classes of cleanrooms and the peak electrical load from each class for California (Mills et al. 1996).

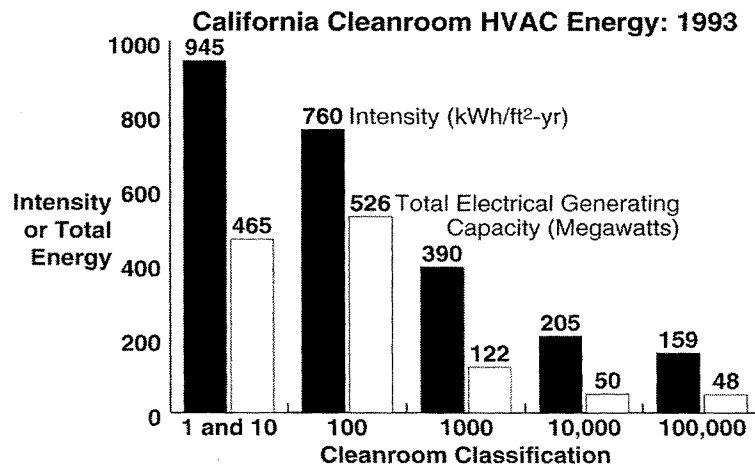


Figure 2. Cleanroom HVAC Energy Use Intensities and Peak Demand Estimates

Most high tech building operators are concerned with their high cost but they do not consider the energy cost to be controllable, and they have little or no basis to determine if their facility is energy efficient or inefficient compared to best practices. Many facilities were designed with limited measurement capabilities making it difficult to determine the actual end-use breakdown for a single system, or for the cleanroom and laboratory portions of a multi-use facility. In addition process and production equipment adds high power densities and is highly variable across facilities. Therefore, energy benchmarking of high tech buildings containing different processes and operating with different environmental conditions (e.g. cleanliness classes), requires development of metrics that go beyond total energy use per square foot.

Frequently owners are interested in energy cost per unit of production. An example of a metric commonly used for this purpose in the semiconductor industry is energy cost per wafer equivalent (of a certain diameter) produced. This metric considers the energy use of the manufacturing process in addition to the facility usage. This number is used to compare the effectiveness of one factory to other factories making the same product within the same company and to evaluate the performance of the same factory over time. This comparison represents one type of evaluation that is possible with metrics, but it is very limited. Other measurements can allow efficiency comparisons across companies and industries:

- One type of system to another type of system providing similar benefits, either within or outside the company,
- One type of system to similar systems at different facilities, or at different times in the same facility,

- A system or component's actual performance to the manufacturer's or designer's specifications,
- A system or component's actual performance to a known benchmark established within an industry or company,
- A system or component to a known "best practice," either within a company or worldwide.

There are important cross-cutting issues that are universal in building benchmarking analysis. One such example is weather normalization. Weather normalization is most widely used to account for changes in weather over time in a single building. For example, pre-retrofit and post-retrofit energy use data are collected and weather normalized to examine energy savings. Weather normalization techniques to compare energy use among various buildings, especially high tech buildings, are less well established. Some buildings are more weather sensitive than others are. Laboratory building energy use is generally thought of as highly sensitive to weather because of the large volumes of outside air used to maintain indoor air quality. Thus, the weather normalization techniques used in a particularly benchmarking strategy will be of significant interest. By contrast, cleanroom energy use is strongly dominated by large quantities of recirculated air, plus high process (tool) loads. Cleanrooms are generally considered less weather sensitive because the percentage of energy use that is weather sensitive, primarily in the make-up air system, is relatively small. Thus, comparing cleanroom energy use among buildings in different climates is likely to be more straightforward.

Benchmarking Techniques

This section outlines four strategies for benchmarking: 1) statistical analysis, 2) point-based rating systems, 3) model-based approaches, and 4) hierarchical end-use performance metrics. We discuss how these approaches are used with office and other commercial buildings, along with comments about how relevant these techniques are for cleanroom and laboratory-type buildings. The final subsection below describes an idealized, hybrid tool combining many of the features of the strategies described.

Statistical Analysis

Figure 3 shows energy use intensities for office buildings, which is a common starting point for benchmarking in commercial buildings. The plot, generated using a prototype research tool developed at LBNL, displays a distribution of energy use intensity (EUI) on the x-axis and frequency on the y-axis. The tool allows the user to input basic building data such as the size, type, and annual energy use. The tool then displays the EUI of a given building compared to the buildings of the same type and size from the same census region. One can determine whether a given building has a high, low, or typical energy-use intensity compared to others. These histograms are based on the US DOE's Energy Information Administration's Commercial Building Energy Consumption Survey (CBECS, US DOE, 1995). CBECS is based on a survey of nearly 6000 commercial buildings spread through the nine US census regions. The data include major building characteristics, such as size, type, presence of certain equipment, hours of use, and annual energy use data.

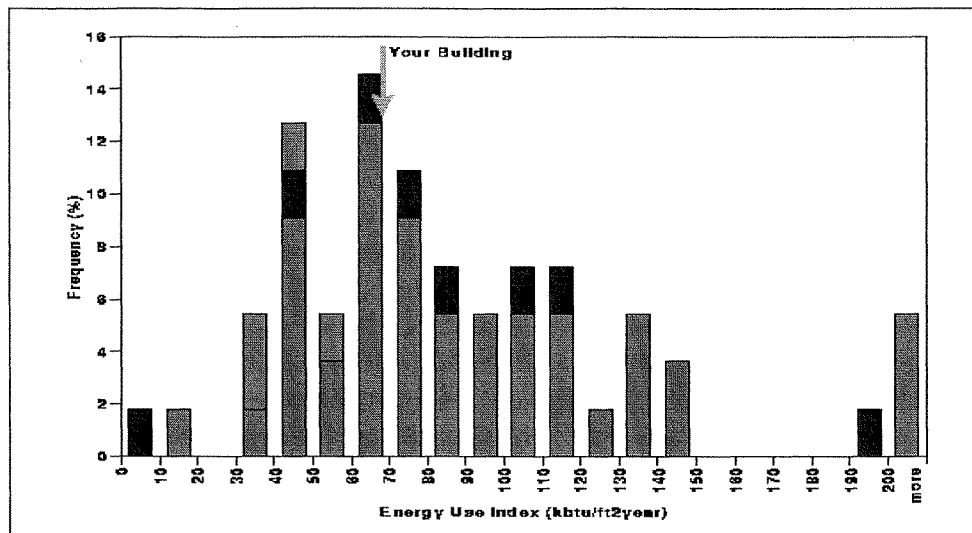


Figure 3. Example of an Energy-Use Intensity Benchmarking Plot. Dark shaded areas show individual buildings for which performance data are publicly available.

The LBNL prototype can be considered a simple starting point for more sophisticated procedures such as the ENERGY STAR[®] Building Label. This label is the most prominent office building benchmarking effort (Sharp 1996, Hicks and Clough 1998), which accounts for differences in the "levels of service" provided by different office buildings, as further described below. The label is based on an analysis of several thousand office buildings in the 1992 and 1995 CBECS survey. Linear regression modeling was used to determine the strongest determinants of energy use. Floor area, number of occupants, connected load (number of PCs), type of occupancy (owner occupied versus leased), and hours operated per week were the most important determinants of energy use, in decreasing order of importance. Additional analysis was done to consider whether the building has a parking garage or computer center, and a weather normalization technique was added. The label analysis algorithm is defined to identify the best 25% of the buildings using a score from 0 to 100. One must get a score higher than 75 to obtain an ENERGY STAR. To actually obtain the ENERGY STAR label, a Professional Engineer must certify that the building meets various performance standards such as thermal comfort, illumination, and air quality.

Statistical benchmarking techniques require large data sets. The CBECS data set is carefully developed to provide a random sample of the entire population of commercial buildings in the U.S. Statistically-based benchmarking techniques using whole building data are unlikely to be effective for cleanroom and laboratory benchmarking because of the uniqueness of each facility and the difficulty of obtaining a large enough random sample set of similar facilities. Statistical data, especially end use data, may be useful for comparisons between buildings of participating companies, however, generalization to the overall population should be avoided.

Point-Based Rating Systems

Another approach to benchmarking is to use a point-based rating system. One example is the US Green Building Council's Leadership in Energy and Environmental Design (LEED) Rating System[™] (USGBC, 1999). The LEED Rating System is a voluntary,

consensus-based, rating system to evaluate environmental performance from a "whole building" perspective, providing a framework for defining a "green" building. It is a system where credits are earned for satisfying each criteria. Different levels of green building certification are awarded based on the total credits earned. The system is designed to be comprehensive in scope, yet simple in operation. The LEED system includes specifications and criteria for commissioning, energy efficiency, erosion control, indoor air quality, thermal comfort, plus water conservation and quality. LEEDs does not allow one to quantitatively compare their buildings against others. It does, however, outline a series of "best practice" standards and guidelines that can be used to evaluate how "energy efficient and environmentally sustainable" an overall facility is. The commissioning and energy efficiency criteria are based primarily on public commissioning guidelines and building codes. LEEDs is a tool for evaluating designs (i.e. in new construction) and is less well suited for on-going benchmarking and performance tracking.

A flexible point-based rating system would be an excellent tool for establishing qualification criteria in a high tech buildings recognition program. Further points could be awarded for participation in quantitative benchmarking and performance tracking programs. The LEED Rating System would need to be modified for optimal use with cleanrooms and laboratories.

Model-Based Benchmarking

The University of California Center for Environmental Research (CEDR) examined methods for laboratory benchmarking and concluded that there are two major problems associated with comparing a given building with a set of similar laboratory buildings (Federspiel et al. 1999). First, only similar buildings can be compared. Second, the entire population may be inefficient. Both of these limitations are significant issues for laboratory buildings because there is no public domain data set for benchmarking like CBECS.

The possible inefficiency of an entire population leads to the question of how do we identify an "efficient" building? Both efficient equipment and an integrated system need to be present, and they need to be operated efficiently.

CEDR constructed a benchmark tool that calculates the minimum energy requirement for a basic set of functional laboratory requirements. This benchmark is computed based on an idealized model of equipment and system performance. An "effectiveness metric" is then computed by dividing the model-based benchmark by the actual energy consumption (Figure 4). The effectiveness metrics from multiple buildings can then be compared to each other. The model converts simplified functional requirements into minimum energy requirements. The data requirements for the model are designed to be easily collected with no sub-metering. They include:

- Location (which relates to weather conditions)
- Indoor air change requirements
- Lighting and HVAC characteristics
- Temperature and humidity requirements
- Occupancy and schedule
- Process equipment

One challenge in cleanroom and laboratory-type buildings is process (tool), or plug-load estimates. Overestimates of process loads are common because they are often based on

nameplate power requirements, which result in oversized and inefficient cooling equipment (Brown, 1996). Laboratories and cleanroom HVAC systems may be intentionally over-sized — to allow for uncertain future build-out or additional process equipment. Ideally benchmarking will facilitate better estimates of process loads in the future.

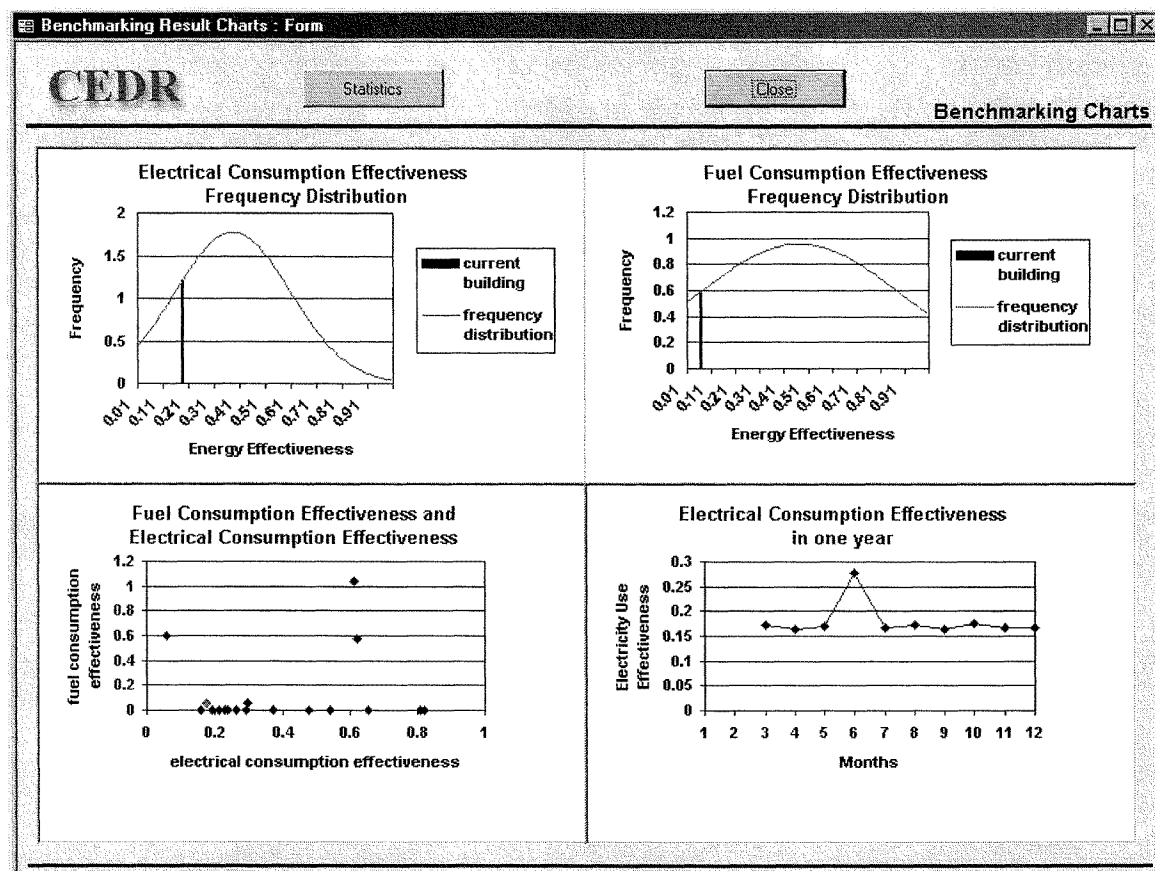


Figure 4. Display of Performance Metrics

The CEDR tool has been developed with laboratory building data for Northern California including climate data for this region. The tool could be enhanced to include a database of U.S. climate data and tested for robustness with a larger set of laboratory buildings. In addition, the model could be refined to include filtration requirements of typical cleanrooms, as well as an estimate of process loads and a breakout of space usage by type (office, lab, cleanroom, etc.). If the approach is found to be robust, it is an attractive methodology for cleanroom and laboratory-type building energy benchmarking.

Hierarchical and End-Use Performance Metrics

Another possible benchmarking methodology is to develop a set of hierarchical and end-use performance metrics. Table 1. illustrates three levels of data which could be used for a laboratory, starting with simple, annual whole-building metrics that are readily available from utility bills and building plans. Level 2 lists a set of data requirements that include additional details about the type of laboratory, percentage of office space within the building,

HVAC characteristics, and maximum annual electric demand. These data allow the generation of metrics that begin to link energy use to the climate and functional requirements. The third level down requires monthly utility bills and weather data. These data are used to examine the weather sensitivity of the building.

Table 1. Tri-Level Benchmarking Data Requirements and Associated Performance Metrics

Level 1. Gross Annual Data Requirements <ul style="list-style-type: none"> Gross sqft. Annual Fuel & Electricity Energy & Cost 	Level 1. Gross Annual Metrics <ul style="list-style-type: none"> Total kBtu/sqft; fuel kBtu/sqft; kWh/sqft Total \$/sqft, fuel \$/sqft., elec. \$/sqft
Level 2. Add Demand & Building Attributes <ul style="list-style-type: none"> Location; Lab type; % office vs. lab Design air flow (cfm); supply air pressure rise Chiller tonnage; HVAC type Max kW 	Level 2. Additional Annual Metrics & HVAC Sizing <ul style="list-style-type: none"> Cfm/sqft; chiller tons/sqft; fuel kBtu/cfm; fuel \$/cfm Elec. kWh/cfm; Elec. \$/cfm Total kBtu/cfm; Total \$/cfm Annual max W/sqft ; W/cfm max Load factor (avg. kW/max kW) Estimated peak cooling load/sqft* Estimated peak cooling load/capacity
Level 3. Add Monthly Data & Weather Normalization <ul style="list-style-type: none"> Monthly Fuel (kBtu) Month Elec. (kWh) Monthly kW Max Monthly Weather (Avg. OSA Temp) 	Level 3. Add Monthly Data & Weather Normalization <ul style="list-style-type: none"> Fuel base load (kBtu/sqft) Fuel weather dependent load (kBtu/HDD-sqft) Elec. base load (kWh/sqft) Elec. weather dependent load (kBtu/CDD-sqft) Metrics based on cfm as opposed to sqft normalizations

* For example, one could estimate peak cooling load using design cfm, design delta temp. for local climate zone, and max. kW adjusted for estimated AC consumption.

Additional levels of data might include:

- **Level 4. Metrics Refined with Hourly Data** - Hourly energy use data along with hourly weather data.
- **Level 5. Metrics Refined with Disaggregated End-Use Data** - Monthly end-use energy measurements such as HVAC, lighting, and plug or process loads.
- **Level 6. Metrics Refined with Disaggregated Hourly End-Use Data** - (a combination of Level 4 and 5) component data such as fan kW, airflow, water-flow, and temperature differences (to measure load, delivered to a building or space), water flow and temperature rise (to measure chilled water cooling tons).
- **Level 7. Other** - Air and water flow pressure drops.

The idea of hierarchical measurements and metrics is to begin at the highest (whole-building) level and begin to "peel the onion" as one moves down to the underlying system performance data. Such an approach is often necessary for identification of specific energy efficiency opportunities for a given facility. While these measurements are clearly important, there is another set of characteristics data to help "explain" the measurements by relating the data back to the "type" of system in place, or the building characteristics. Data collected should also include hours of use, equipment type and vintage, plus process and plug load description.

Whole building level data (levels 1-4) may give false signals – a low energy use intensity may not mean an energy efficient building. Disaggregated data (level 5-6) is very useful in understanding energy consumption in high tech buildings, and allows for benchmarking of systems and components across multiple buildings (and industries). For example, kW/ton and W/cfm are useful benchmarks that can be applied across different load conditions and plant configurations. However, such measurements are expensive to obtain, and are therefore not widely available.

Hybrid Approaches and Ideal Tools

Another strategy for a benchmarking methodology is to draw upon the best aspects of the four primary approaches to create a hybrid approach. We can conceptualize how an ideal benchmarking tool might function in order to guide research and data collection needed to build such a tool. The tool may have three modules:

1. Whole building data and metrics
2. End use data and metrics
3. Performance rating

Consider how the tool might react to both an inefficient (Lab A) and an efficient laboratory building (Lab B). Starting with Lab A (the inefficient building) we input a series of features such as the size (broken down by usage type), hours of use, location, and HVAC design information, plus a year of monthly utility bills. The tool responds with an EUI distribution plot for buildings with similar characteristics for a given climate. We might find the building to be in the highest EUI quartile and be concerned that the tool has suggested that the building is not efficient compared to others. Knowing that this statistical analysis may be tenuous, the tool also produces a model based energy effectiveness ratio. This indicates that the building uses 2.5 times more energy than “best practice.” At this point we’re pretty sure our building could be improved but we don’t know where to start looking for opportunities. Based on a measurement plan generated by the tool, we then submit the next level of input data requested (module 2). Here we enter short term (one week) end use monitoring data and additional design data. We provide estimates for any data we couldn’t obtain directly and make adjustments to the design data for known changes in the as-built conditions. The tool responds with an EUI distribution plot for (end use) systems. We find the chiller plant, at 1.5 kW/ton to be in the highest EUI quartile. In addition we find that the chiller and boiler operate simultaneously. Even when the outdoor temperature was below 55 degrees F, the chiller was consuming 50 kW, or 25% of its rated input. The benchmarking tool has helped us identify an inefficient cooling plant in Lab A. Using the refined data inputted into module 2, the tool recalculates the energy effectiveness ratio. Much to our surprise it has decreased to 2.3 times best practice – not as bad as we originally thought, but still not very good.

In the case of Lab B (the efficient building), we input our data into module 1 and find we’re in the lower quartile on the EUI distribution curve. This finding offers some comfort since the building is only two years old and a concerted effort was made to ensure that efficient design principles were incorporated, properly commissioned, and continuously monitored. Desiring some recognition for a job well done, we go to module 3, a point based rating system. Module 3 takes some of the information that we have already entered, but in addition to quantitative performance, this module includes a series of inputs that describe

features of the building that would explain its good performance. We easily qualify for the “silver” rating but we need 2 more points for the “gold.” We find that we can pick up those two points if we install the heat recovery coil that was removed from the design during a last minute “value engineering” exercise.

There are several additional features an ideal benchmarking tool might provide:

- **Multiple parameter visualization.** The ability to display the data with a variety of axis and parameters similar to those shown in Table 1, such as energy cost per square foot or energy cost per cfm, etc.
- **Design guide benchmarks and engineering rules-of-thumb.** Compare the data in the database with common engineering rules-of-thumb and best practices, such as tons/cfm, cfm/sqft, etc.
- **Web-links for further resources.** The tool offers a series of links to web sites that discuss retrofit strategies and options.
- **Identification of showcase buildings within EUI distributions.** Such showcase buildings have web links that take the user to detailed "best practice" case studies to illustrate efficient design and operating strategies.

Discussion

Benchmarking Strategies for Federal Laboratories

A recent US Executive Order (13123) sets a 25% energy savings target relative to 1990 for federal laboratories. An important concept here is baselining. Federal agencies have to establish a baseline year to measure savings against. Weather-normalization techniques are important in such activities, but other types of changes that explain energy use over time need to be examined as well. One difficult area to track is changes in process loads. It is likely that many of the labs and cleanrooms may utilize different equipment, and usage rates, thus confounding the analysis of energy savings. One strategy that should be considered is sub-metering of process loads, following the hierarchical performance metrics approach outlined above. Design standards for new DOE buildings now require the ability to sub-meter process, HVAC, and lighting loads. A second activity that is likely to prove useful for federal agencies is to perform some statistical comparison of energy intensity distributions among a set of buildings. Such a comparison should allow the identification of the most energy intensive facilities that may have the greatest energy savings potential.

Benchmarking for Laboratories for the 21st Century

Laboratories for the 21st Century (Labs21) is a new EPA & DOE initiative to: 1) establish voluntary goals for energy performance, 2) set criteria for recognition, and 3) provide energy management tools for public and private sector laboratory buildings. Labs21 is committed to establishing a national energy performance database for laboratories. This will most likely utilize whole building data (no sub-metering), however it may utilize both statistical and model-based benchmarking. In addition, the initiative will establish criteria for recognition. The recommended approach for this program is to use a point-based system. The point system could recognize the presence of energy efficient design features (such as heat recovery, VAV fume hoods, etc.), as well as give credit for utilizing performance

monitoring features (e.g. sub-metering of important end-uses). Thus, this program will likely examine a hybrid approach.

PG&E Cleanroom Benchmarking

PG&E is sponsoring a cleanroom benchmarking project to assess energy use and energy savings opportunities. This project resulted from a study that showed electronics (high tech) and biotechnology as two large and growing markets, and requests from these customers for energy benchmarking information. Both industries are energy intensive due to their cleanroom facilities. The effort will characterize energy use of the cleanrooms separately from the larger buildings or complexes they are in. Further PG&E will evaluate the performance of some central plant systems. The project involves conducting a series of short-term measurements in several cleanrooms of various cleanliness classes and industries. A series of metrics have been developed to assist in characterizing performance. Examples of measurements include HVAC efficiencies (for all components such as chillers, cooling towers, pumps, etc.), and air flow characteristics including pressure drops, air movement efficiency (cfm/kW), and coil face velocity (ft/min).

A modified hierarchical approach will be used, beginning with whole-building energy use and progressing to system-level measurements, and then to key component measurements. The plan and its execution will be tailored to each individual site with the objective of collecting data to as great a detail as practical within a limited budget and a short period of time. In this way, the systems, and level of detail, will be prioritized. In some respects data will be collected where it is opportunistically feasible and ignored where it is not. The overall goal will be to populate a database with as much of the pertinent energy use data as practical. Comparison data will be available for all the high priority data points. If measured data is not available, design data, data from the test and balance report, or certification report data will be utilized.

A challenge of this benchmarking project will be in consistently defining the cleanroom envelope and the boundary of the benchmarking study. Since the goal of the program is to compare only facility systems' energy use for a given cleanliness class of cleanroom, it will also be important to accurately account for the process and/or plug load effects so that only the facility systems of interest are included. Systems and components that account for small (say less than 5%) facility energy use will be ignored, with the possible exception of lighting systems, which are expected to have some attractive opportunities even though their relative magnitudes of saving are low.

The data will be analyzed to begin determining best practices and relative ranges of operating parameters. Once a robust data set is available, building operators will be able to gauge the relative performance of their building as a whole and individual system performance as well.

Conclusions

We have reviewed four techniques used for building energy performance benchmarking of cleanroom and laboratory buildings. There are strengths and weaknesses to each approach. A multilevel hybrid approach that utilizes statistical, modeling and a point

system may be possible for evaluating the overall performance of cleanroom and laboratory-type buildings.

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