Advanced Benchmarking for Complex Building Types: Laboratories as an Exemplar

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ABSTRACT

Complex buildings such as laboratories, data centers and cleanrooms present particular challenges for energy benchmarking because it is difficult to normalize special requirements such as health and safety in laboratories and reliability (i.e. system redundancy to maintain uptime) in data centers which significantly impact energy use. For example, air change requirements vary widely based on the type of work being performed in each laboratory space.

We present methods and tools for energy benchmarking in laboratories, as an exemplar of a complex building type. First, we address whole building energy metrics and normalization parameters. We present empirical methods based on simple data filtering as well as multivariate regression analysis on the Labs21 database. The regression analysis showed lab type, lab-area ratio and occupancy hours to be significant variables. Yet the dataset did not allow analysis of factors such as plug loads and air change rates, both of which are critical to lab energy use. The simulation-based method uses an EnergyPlus model to generate a benchmark energy intensity normalized for a wider range of parameters. We suggest that both these methods have complementary strengths and limitations.

Second, we present “action-oriented” benchmarking, which extends whole-building benchmarking by utilizing system-level features and metrics such as airflow W/cfm to quickly identify a list of potential efficiency actions which can then be used as the basis for a more detailed audit. While action-oriented benchmarking is not an “audit in a box” and is not intended to provide the same degree of accuracy afforded by an energy audit, we demonstrate how it can be used to focus and prioritize audit activity and track performance at the system level. We conclude with key principles that are more broadly applicable to other complex building types.

1. Introduction

Over the past few years, there has been a significant increased interest and activity in commercial building energy efficiency benchmarking. Most notable has been a flurry of new regulations passed by national, state and local governments. These include the European Performance of Buildings Directive which requires all buildings with significant public access to display their energy performance; Assembly Bill 1103 in California which requires all commercial buildings to disclose their energy performance at the time of sale or lease; EISA 2007 which requires all U.S. government buildings to be benchmarked on an ongoing basis; and local regulations in cities such as New York which require all municipal buildings to be benchmarked. In addition, voluntary benchmarking programs continue to grow in both government and utility programs.

One result of this trend is that the scope of these programs has broadened beyond "typical" commercial buildings such as offices, schools, hotels and retail buildings to include specialized buildings such as laboratories and data centers which were not addressed in earlier programs. Another result of this trend is that there is growing scrutiny of the technical methods underlying benchmarking programs, e.g. in mandatory programs, particularly, there is increased interest from diverse stakeholders in the datasets used for comparisons and how energy use is normalized and represented.

Energy benchmarking has been effectively used for comparing the energy use of offices, schools, and other commercial facilities, most notably in the ENERGYSTAR program. However, there have been limited efforts thus far to benchmark laboratory facilities and no national efforts akin to ENERGYSTAR. This is partly due to the fact that laboratories constitute a fairly small part of total U.S. building energy use, and have not attracted the attention of national programs such as ENERGYSTAR.

What's so special (and not) about energy use in laboratories?

Laboratory facilities are highly energy intensive and have significant opportunities to improve energy efficiency. While laboratories have several efficiency opportunities that are common to other commercial building types (e.g. chiller and boiler plant efficiency, high efficiency lighting), they also have some special considerations. Health and safety requirements such as minimum air change rates significantly impact energy use. Equipment loads are highly variable depending on the type of laboratory – as low as 2-3 W/sf in some chemistry labs to as high as 15 W/sf in some physical laboratories. As a result, HVAC is the major area of efficiency opportunity and lighting and envelope have a relatively small impact. Furthermore, some of the key HVAC efficiency opportunities have unique applications in laboratories (e.g. low-flow fume hoods, energy recovery systems configured to handle hazardous air streams).

Labs21 Benchmarking tool

Labs21[1] developed a web-based database tool to collect, analyze and display benchmarking data on laboratories (http://labs21benchmarking.lbl.gov/). The tool allows users to benchmark their facility using a range of building and system level metrics as shown in Table 1.

Table 1: Benchmarking metrics available in the Labs21 benchmarking tool

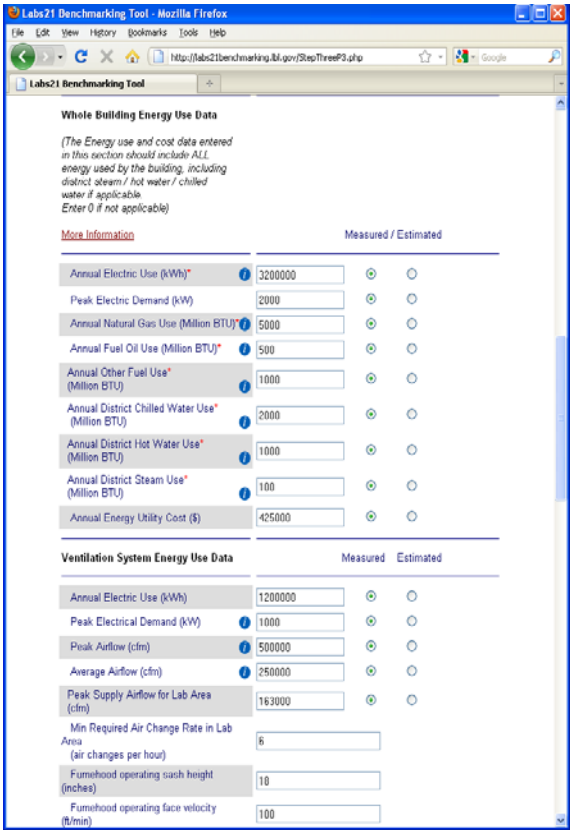
System	Metrics	
Total Building	Btu/gsf-yr (source) Btu/gsf-yr (site) $/gsf-yr (site)	Peak W/gsf (elec) kWh/gsf-yr (elec)
Ventilation	kWh/gsf-yr Peak supply cfm/sf(lab)	Peak W/cfm Avg cfm/peak cfm
Cooling	kWh/gsf-yr Peak W/gsf	Peak gsf/ton Installed gsf/ton
Lighting	kWh/gsf-yr Peak W/gsf	Installed W/sf(lab)
Process-Plug	kWh/gsf-yr Peak W/gsf	Peak W/sf(lab)

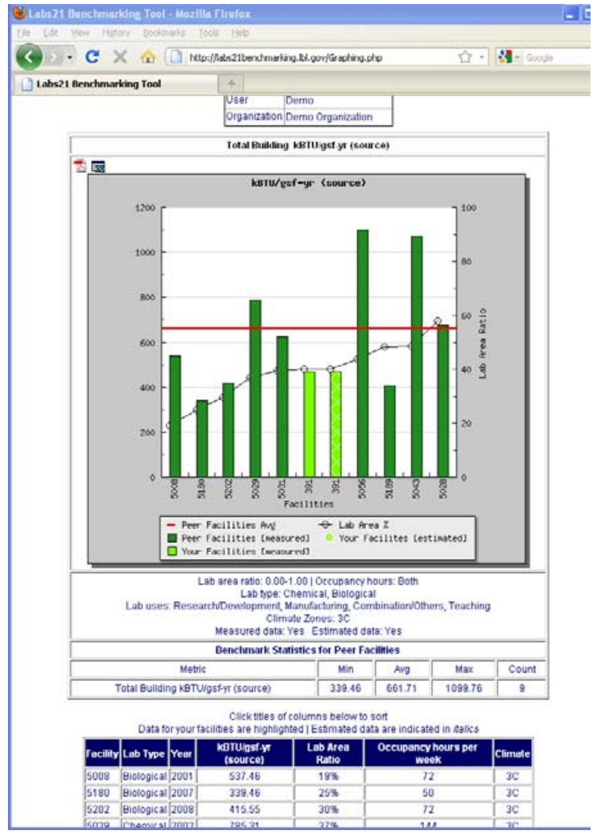
Figure 1 shows a portion of the data input form (left) and the results page (right). In order to perform data analysis, the user specifies a metric of interest and selects a peer group of buildings for comparison by filtering the dataset based on the following criteria:

- Lab area to gross area ratio: ratio of the lab area requiring 100% outside air to the gross facility area.
- Occupancy hours per week: ‘Standard’ (≤ 80 hrs/week) vs. ‘High’ (>80 hours/week).
- Lab Type: Chemical, Biological, Chemical/Biological, Physical, Combination/Other
- Lab Use: Research & Development, Teaching, Manufacturing, Combination/Other
- Climate zone. 15 climate zones in the United States based on Briggs et al. (2002).
- Measured and estimated data included in the dataset: Users may choose to exclude estimated data from the peer group.

Figure 1: Labs21 benchmarking tool input screen (left) and output (right)

[1] Labs21 refers to the Laboratories for the 21st Century program which is sponsored by the U.S. Department of Energy’s Federal Energy Management Program and the U.S. Environmental Protection Agency. Labs21 develops and provides tools, training and technical assistance for the design and operation of high-performance laboratories.





The peer dataset currently includes over 200 facilities drawn from a wide range of laboratory owners and operators in the United States, including federal government agencies, universities, pharmaceutical companies, and other organizations. The peer dataset also includes selected buildings from the U.S. Department of Energy's CBECS dataset[2] (EIA 2003). Although the Labs21 dataset is larger than the CBECS laboratory data set, it should also be noted that the Labs21 dataset is not necessarily a statistically representative sample of the U.S. laboratory building stock. The non-CBECS facilities in the Labs21 dataset tend to be larger and more energy intensive labs, most of which are chemical and biological labs. While the CBECS dataset represents a statistical sample of the U.S. building stock, the data on laboratory buildings is very limited and therefore inadequate for benchmarking. While the Labs21 dataset continues to grow with joint marketing efforts by Labs21 and ENERGYSTAR, data collection remains a challenge and system-level data are especially difficult to obtain as most facilities do not sub-meter end uses.

[2] CBECS has 43 buildings classified as "laboratory" of which 14 are included in the Labs21 tool. The remaining 29 were excluded for one of the following reasons: energy use was estimated (not actual); location could not be narrowed to one of the 15 climate zones; buildings served by district chilled water (CBECS does not report district chilled water use).

2. Key Benchmarking Considerations

The core of the methodological choices in benchmarking pertain to two issues: a) the parameters that are used to normalize the efficiency metric; and b) the methodology used to normalize the metric.

Table 2 describes the key normalizing parameters that should be considered for laboratory buildings.

Table 2 Key normalizing parameters for laboratories

Parameter	Notes
Gross area	Total area of conditioned spaces (laboratory and non-laboratory)
Lab area	Net area of laboratory spaces (areas requiring 100% outside air)
Climate	
Lab type	Chemical, biological, physical, combination, other
Lab use	Research, teaching, manufacturing, other
Occupancy schedule	Some manufacturing facilities operate 24/7
Min. ventilation rates	Minimum ventilation rates vary depending on lab use and risk factors
Equipment loads	Equipment loads can vary widely based on the type of activity

It is important to note that some of these parameters may well present efficiency opportunities themselves. Normalizing for these parameters should take into account:

- Ventilation rates: The definition and interpretation of what is actually "required" varies considerably across different codes and standards, even for the same lab type. Reducing ventilation rates is often an efficiency opportunity (Labs21 2008).
- Schedules: It is important to distinguish between occupancy schedules and operation schedules. It is common for some facilities to operate their building systems 24/7 even if their occupancy schedule is not 24/7. Therefore, there may be efficiency opportunities in system turndown.
- Equipment loads: Equipment loads in different types of laboratories can vary widely. Although equipment loads are usually seen as a functional requirement, there are efficiency opportunities such as turning off equipment when not in use. Normalizing for this metric can be challenging because actual equipment loads are difficult to measure and design values should not be used because they are often grossly overestimated (Labs21 2007).

The Labs21 tool allows the user to select a peer set of buildings with similar characteristics by filtering the data set. This "slice and dice" approach is essentially a crude form of normalization. More rigorous normalization is typically done with either a regression-based approach or simulation model-based approach. The next two sections describe these approaches as applied to the Labs21 dataset.

3. Empirical Benchmarking using Regression Analysis of Labs21 dataset

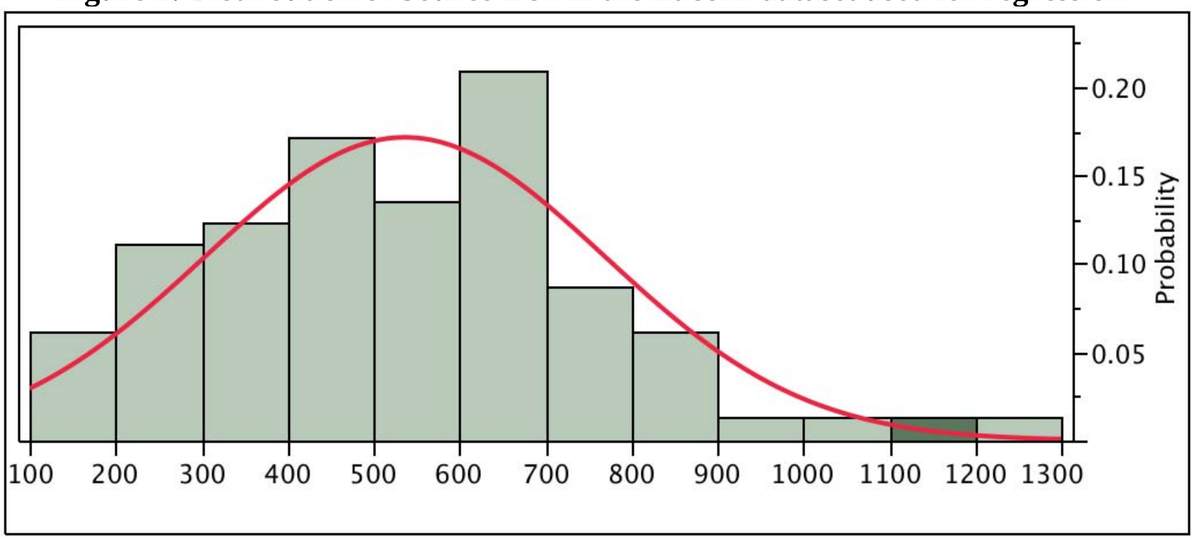
In this approach a multiple regression model is developed from a dataset and expressed as an equation that relates the efficiency metric (e.g. source kBtu/sf-yr) to normalizing parameters (gross area, etc.). This equation is then used to compute normalized energy use against which actual energy use can be compared. This approach has been applied to the CBCES dataset (Sharp

1996) and is used in ENERGYSTAR (ENERGYSTAR 2007). It works well provided there is a large enough representative dataset with normalizing parameters to run a regression analysis.

We performed a regression analysis on the data in the Labs21 database. At the time of our analysis, the regression data set consisted of 174 buildings with measured building –level energy use data. Data for the Labs21 database has been added over a several year period. The type of data that has been collected has evolved and grown as the program has matured. Early energy use data ("early group") consisted only of electrical and fuel use. More recent data ("later group") has fuel broken into gas, fuel oil, district hot and chilled water or steam, and other fuels. Analysis showed that the two groups were not equivalent. Energy use in the early group was significantly higher (+31%, probability = 0.01%) than that of the later group. Furthermore, the regression results for the two groups were different, and the correlation coefficient of the early group was substantially lower than for the later group (R^2 of 19% versus 34%). These differences are consistent with our concern about the accuracy of the data in the early group, and we therefore limited our subsequent analysis to just the later group consisting of 82 buildings.

The normalized benchmark metric is source kBtu/sf-yr. For the 82 buildings in our analysis the mean and standard deviation for this metric were 537 ± 233 kBtu/sf-yr (Figure 2). The quartile values are 107, 363, 528, 681, and 1254 kBtu/sf-yr.

Figure 2: Distribution of Source EUI in the Labs21 dataset used for regression



Although this distribution could be used directly to set a benchmarking target, it misses some significant sources of variation. Independent variables for which we had complete or almost complete data were: lab use, lab type, climate zone, gross area and lab area, year built, fractional energy use split (electricity, fuel oil, etc.), and weekly occupancy hours. We also used zip code data to estimate heating and cooling degree days (65°F base) for each of the buildings. Lab type, fraction lab area (lab area/gross area), and weekly occupancy were significantly correlated to energy use. We were surprised that the climate variables were not correlated to energy use. At this stage, we can only hypothesize that buildings may be sufficiently tailored to their climates that climate does not remain a significant factor to energy use.

The fit with the significant variables is as follows:
Source kBtu/sf-yr = 546 + K(lab type) + 237 x (LF- 0.4285) + 2.82 x (WO – 79.5)
where:
WO = weekly occupancy in hours,
LF = lab area/gross area, and
K(Biological lab) = 66,
K(Chemistry lab) = 83,
K(Chemistry/Biology mixed) = 56,
K(Combination/Other) = -127, and
K(Physical lab) = -77.

The fitted values of energy intensity ranged from 280 to 866 kBtu/sf-yr. This represents a variation of 330 to 260 kBtu/sf.yr around the mean of 537 kBtu/sf.yr described earlier. This makes benchmarks based on the regression better able to identify lab buildings that are significantly worse than their peers at utilizing energy.

It should be noted that the independent variables in the regression are not efficiency variables. A fit with an R^2 of 1 based on these variables would indicate that there were no differences in efficiency among the measured buildings. The actual fit had an R^2 of only 34% and a standard deviation of 196 kBtu/sf.yr. Further work will be required to get an estimate of how much of the remaining 66% of the variance is due to efficiency differences and how much is due to operational or other variables. Successful benchmarking depends upon having a significant fraction of this remaining variance being due to efficiency differences. However, even if much of the variance is due to efficiency differences there is still a potential problem if even the most efficient lab in the dataset is inefficient in a practical sense. If the entire population is inefficient, it will cause inefficient buildings to be rated as efficient. In the case of laboratory buildings this is of particular concern because energy efficiency has not permeated laboratory design as it has other commercial building types.

4. Simulation-based Benchmarking using Labs21 EnergyPlus model

A simulation-based benchmarking approach has the potential to address many of the limitations of the regression-based approach described above. In this approach, a simulation model is used to calculate a benchmark energy use representing a "best practice" case against which the actual energy use can be compared. The model can account for a number of normalizing parameters including those that may not be available in the empirical dataset. Federspiel et al. (2002) explored described a model-based approach using a simplified analytical model of a laboratory. Labs21 explored a simulation-based approach using a DOE-2 model (Mathew et. al 2004). In this paper we describe further development and analysis of this approach using an EnergyPlus model for generating the benchmark.

Labs21 EnergyPlus Benchmark Model

In laboratory facilities, it is critical to distinguish between lab spaces and non-lab spaces, because they have significantly different operational characteristics, building systems and resulting energy use. The Labs21 Benchmark Model is an EnergyPlus model that has two separate building modules, one for each space-type. Each module has a separate HVAC system with a shared central chiller and boiler. The enclosure, HVAC, and lighting specifications reflect best practice efficiency, as the model is meant to generate a best-practice benchmark against which energy use for a given building can be compared.

We implemented an Excel interface to the EnergyPlus model that allowed us to vary a number of parameters including location, lab area ratio, occupancy hours, minimum air change rate and plug loads. To generate a benchmark value for a given facility, the model is run with parameter values that correspond to that facility. The modeling results are post-processed and presented in the Excel interface including benchmark values of total energy intensity and end-use energy intensities.

We ran a number of tests to validate and adjust the model. First, we compared the simulated data against the empirical data from the Labs21 dataset and verified that the simulated energy use benchmarks are within range of the actual energy use of the most efficient facilities in the dataset. Second, we ran a number of parametric analyses to ensure that the model responds appropriately, based on experience, to variations in parameters (e.g. an increase in air change rates creates an increase in fan energy, etc.). Finally, we compared the end-use breakout for the simulated results with the end-use breakouts for selected facilities in the dataset for which we had data.

The benchmark energy intensity can be compared to the actual energy use with the energy benchmark ratio (EBR):

EBR = benchmark energy use / actual energy use

EBR will usually be a value between 0 and 1, although it can be greater than one if the subject facility is more efficient than the benchmark. A higher value of EBR indicates a more efficient facility. EBR can be calculated for electricity, fuel, total site energy, and total source energy. The EBR for different facilities can be compared to each other, as it is a normalized metric.

Case study: simulation-based benchmarking vs. simple data filtering

We present a case study comparing filter and simulation based benchmarking for 15 facilities from the Labs21 database. These facilities were selected by filtering the database based on the following criteria: climate zone 4A ("Mixed-Humid"); chemical, biological, and chemical/biological lab types; lab area ratios between 0.4 and 0.6; standard occupancy hours (≤80 hours per week). The Labs21 database returned the annual energy use intensity (EUI) for each of these facilities. The EUI for each facility was benchmarked against the average EUI for all 15 facilities by calculating the deviation from the average as follows:

dev(EUI) = (mean(EUI) – EUI) / mean(EUI)

We then ran the simulation-based analysis by modifying the Labs21 EnergyPlus benchmark model for each of these facilities, varying the location (i.e. specific cities within climate zone 4A), lab-area ratios and occupancy schedule to correspond to each of the fifteen facilities. We then calculated the energy benchmark ratio (EBR) for each facility, using the formula above. The EBR for each facility was benchmarked against the average EBR by calculating the deviation from the average as follows:

dev(EBR) = (EBR – mean(EBR)) / mean(EBR).

The definitions for dev(EUI) and dev(EBR) ensure that in both cases, a positive deviation represents a facility that performs better than average.

Figure 3 shows the EUI and EBR deviations for the fifteen facilities in the case study, sorted in decreasing order of dev(EUI). As expected, the trends for dev(EUI) and dev(EBR) are similar. However, it is clear that the change from filter to simulation based benchmarking has a significant impact on several facilities' ranking with respect to their peers (Table 3). For instance, the facility ranked 7th out of fifteen based on the dev(EUI) had an EUI almost exactly equal to the average EUI. In the model-based approach, however, this facility's EBR is 23% below the average, earning it the rank of 11th out of fifteen. This downward shift is likely due to the fact that this facility is located in a milder climate within the 4A climate zone, and has lower occupancy hours relative to its peers.The model-based benchmarking normalizes for these variations *within* the coarser filter settings i.e. milder climate within zone 4A and lower occupancy hours *within* the 'standard' (≤80 hours per week) occupancy hours category.

Figure 3. Comparison of filter- and model-based benchmarking results.

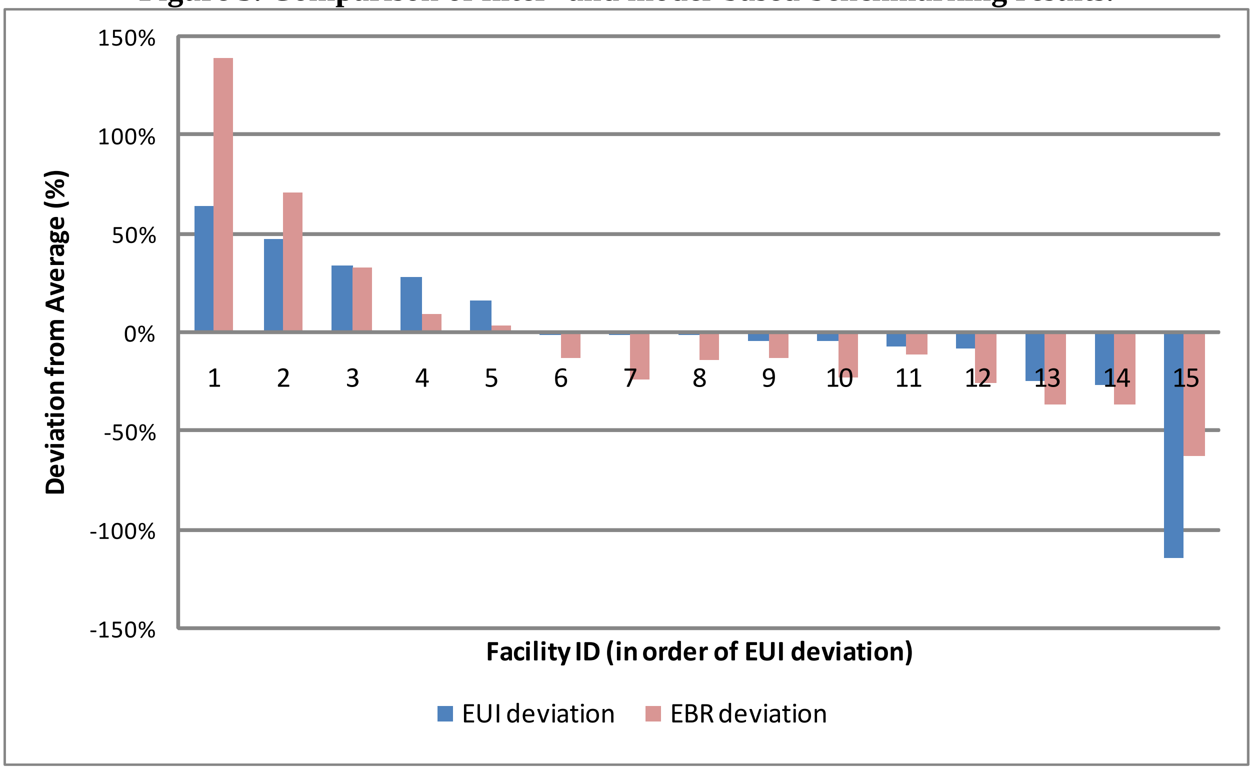


Table 3. Difference in energy efficiency rank for filter and model based benchmarking.

Facility ID	EUI Rank	EBR Rank	Rank Change
Facility 1	1	1	-
Facility 2	2	2	-
Facility 3	3	3	-
Facility 4	4	4	-
Facility 5	5	5	-
Facility 6	6	7	-1
Facility 7	7	11	-4
Facility 8	8	9	-1
Facility 9	9	8	1
Facility 10	10	10	-
Facility 11	11	6	5
Facility 12	12	12	-
Facility 13	13	14	-1
Facility 14	14	13	1
Facility 15	15	15	-

3. Action-oriented benchmarking: drill-down beyond whole-building

Action-oriented benchmarking extends whole-building energy benchmarking to include analysis of system and component energy use metrics and features (Mills et al. 2008). It thereby allows users to identify, screen and prioritize potential efficiency opportunities (Figure 4), which in turn can be used to inform and optimize a full-scale audit or commissioning process.

Such action-oriented benchmarking guidelines have been developed for laboratories, cleanrooms and data centers (LBNL 2009). The guidelines for laboratories include 27 system-level metrics. For each of these metrics, the guideline defines performance benchmarks and efficiency actions that can be inferred from them. While a more exhaustive treatment of system level benchmarking metrics is beyond the scope of this paper, we describe one ventilation metric as an illustrative example (Mathew et al. 2008).

Ventilation system W/cfm is defined as the total power of supply and exhaust fans divided by the total flow of the supply and exhaust fans in cfm. It provides an overall measure of how efficiently air is moved through the laboratory, from inlet to exhaust, and takes into account low pressure drop design as well as fan system efficiency (motors, belts, drives). Figure 5 shows the range of ventilation system efficiency at peak loads for various laboratories in the Labs21 benchmarking database, along with benchmark values for different levels of efficiency. There is a wide range of efficiencies, from 0.3 W/cfm to 1.9 W/cfm.

It should be noted that action-oriented benchmarking is not an “audit in a box” and is not intended to provide the same degree of accuracy afforded by an energy audit. However, selected system level metrics can be used to focus and prioritize audit activity and track performance at the system level. They may also be used in new construction to track efficiency over the course of the design process – for example, the Labs21 benchmarking metrics were included as part of the design documents at each stage of the design process for a new research laboratory at the University of California, Berkeley.

Figure 4 Action-oriented benchmarking using a hierarchy of metrics

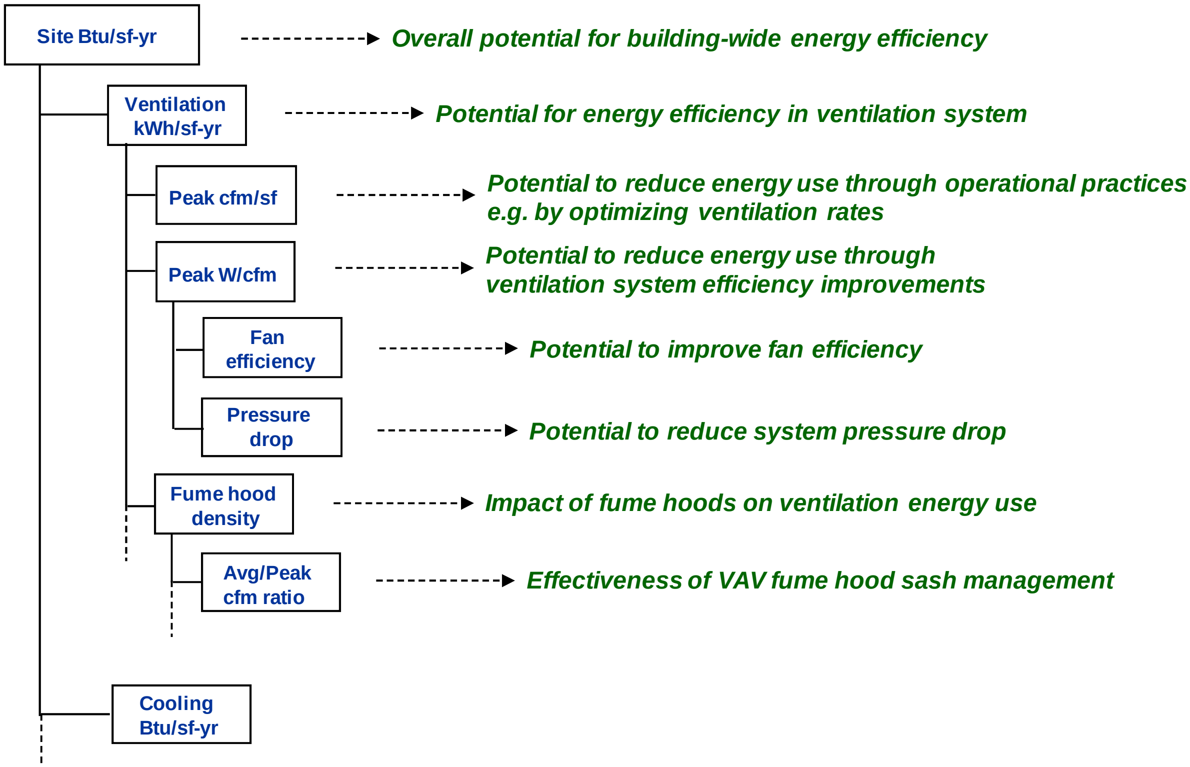
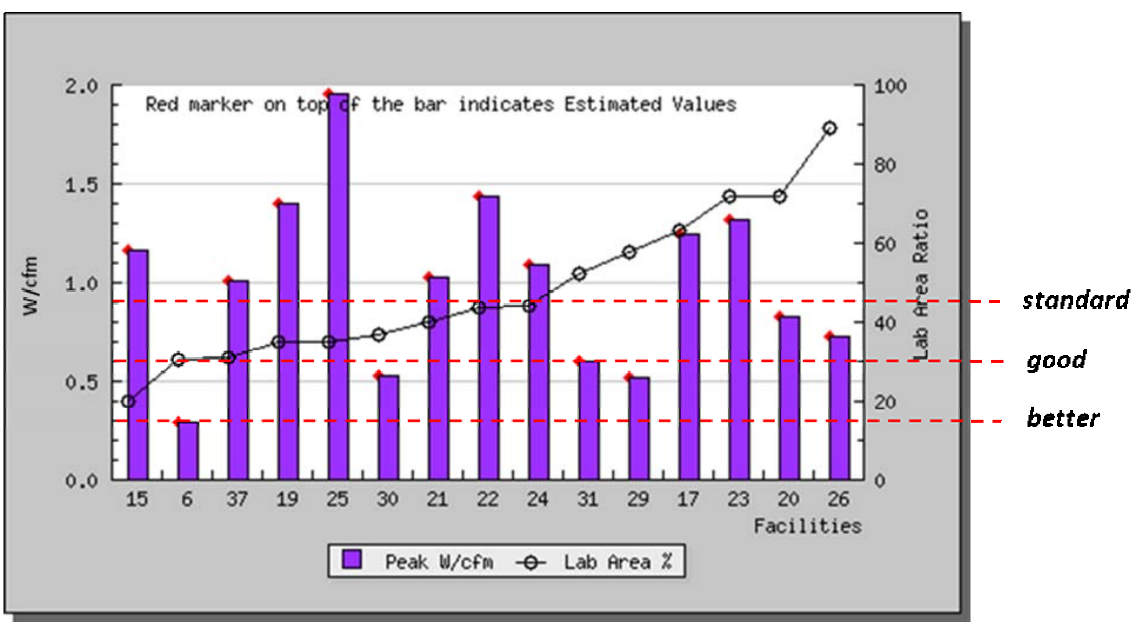


Figure 5. Ventilation W/cfm data from the Labs21 benchmarking database. Benchmarks for standard, good and better practice are based on Labs21 (2005).



Conclusions – Lessons for other complex building types

In this paper we presented three approaches to benchmark laboratory buildings: simple data filtering of the Labs21 database; empirical benchmarking using multiple-regression analysis of the labs21 database; and simulation-based benchmarking using an EnergyPlus simulation model. We also presented the notion of action-oriented benchmarking which extends whole-building energy benchmarking to include analysis of system- and component-level energy use metrics. We summarize below some the key findings that we suggest are applicable to other complex building types such as cleanrooms and data centers as well.

- There are few if any national efforts to collect and analyze energy use data on these building types. CBECS does not address them adequately. As a result, it requires targeted data collection efforts with key stakeholders to collect data in a consistent manner that can be used for benchmarking. Data collection efforts should include facility parameters that are key drivers of energy use in these building types, e.g. fume hoods in laboratories, cleanliness levels in cleanrooms, etc. Labs21 is collaborating with ENERGYSTAR to significantly expand the Labs21 benchmarking database.
- Simple data filtering offers a starting point for benchmarking and may be adequate for some benchmarking applications e.g. initial screening. Its major advantages are that it is transparent and easily understandable in that it does not involve any transformations on the data. However, it may be inadequate for applications that require more rigorous normalization, unless there is a large enough dataset that allows for narrow data filtering.
- Empirical benchmarking using multiple-regression analysis is a proven benchmarking approach. Its major advantage is that it provides a normalized benchmark comparison to actual peer buildings. However, EUIs normalized using multiple regression are less transparent and intuitive than "raw" EUIs. Furthermore, multiple-regression is viable and effective only if there is a large enough dataset that includes relevant normalizing parameters. As noted earlier, this can be a challenge for special building types and reinforces the need to have targeted data collection efforts for these buildings.
- Simulation-based benchmarking offers the possibility of normalizing for a wide range of parameters, and may be the only viable option if empirical data are limited or unavailable. Simulation-based benchmarking provides a rich set of system level data that could be used for benchmarking system and component metrics. However, benchmarks generated from simulations are highly sensitive to modeling assumptions and should be checked for plausibility against empirical data.
- Each of these three approaches has its strengths and limitations, as noted above. They are not mutually exclusive and could complement each other depending on the benchmarking application, data availability, degree of normalization required, etc.
- Whole-building benchmarks are limited in their explanatory power. System-level "action-oriented" benchmarking can be used to illuminate system level efficiency and identify potential actions to improve it.

DISCLAIMER

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