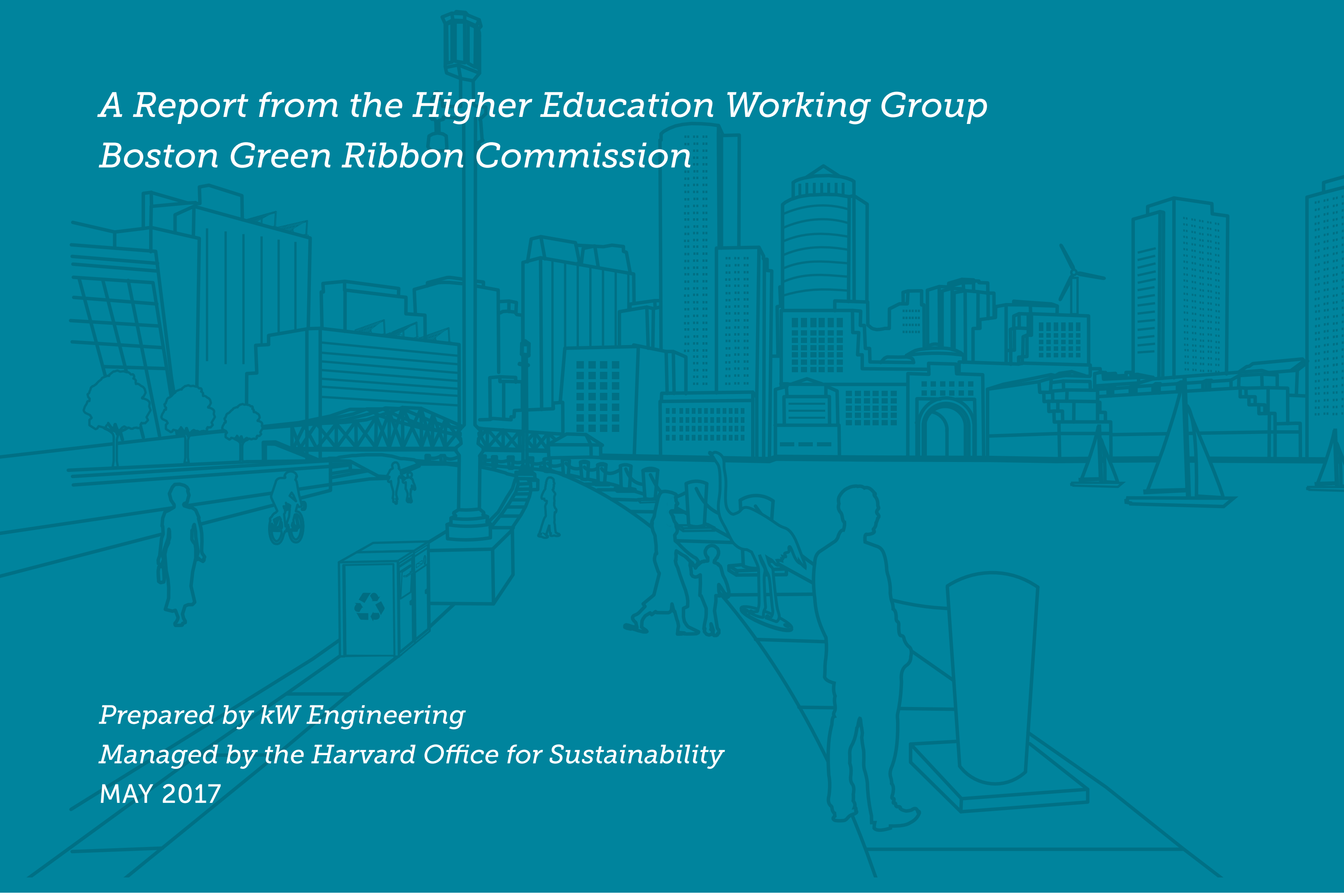
Boston Area Laboratory Energy Benchmarking Study

Year 1 Data Analysis Report: University Labs

A Report from the Higher Education Working Group
Boston Green Ribbon Commission



Prepared by kW Engineering
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BOSTON Green Ribbon COMMISSION | Higher Education Working Group

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kW ENGINEERING

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About the Author

kW Engineering is a nationwide energy engineering consulting firm specializing in saving energy and reducing utility costs. kW's mission is to make all buildings sustainable by improving operation while increasing building value and delivering energy and cost savings.

Report author Alison Farmer delivers energy efficient solutions to kW's high-tech and higher-ed clients, ranging from strategic planning and energy analysis to detailed control system design and commissioning. Alison is a former research astrophysicist who now makes her impact on this planet via a deep dedication to energy efficiency in buildings. Specializing in labs, Alison has chaired I2SL's Lab Benchmarking Working Group since its inception in 2014.

About the Boston Green Ribbon Commission (GRC)

The mission of the GRC is to convene leaders from Boston's key sectors—business, education, health care, non-profit, finance, real estate, professional services, tourism and others—to support the outcomes of the City's Climate Action Plan. The GRC works on a network model and comprises a set of sector-based and initiative-based Working Groups. Together, participants focus on two key strategies: 1) Climate Ready Boston, to help the City become climate resilient and prepared for future impacts of sea level rise, more intense heat, and flooding, and 2) Carbon Free Boston, to develop policy and technology pathways that will enable Boston to reach its goal of net zero carbon by 2050.

About the GRC Higher Education Working Group

The GRC Higher Education Working Group represents the unique constituency of large research and residential campuses in Boston and neighboring cities. Lab facilities are often the source of the greatest energy use at large research institutions, disproportionate to the square footage they occupy, so they are a key area of focus for educational institutions. The Higher Education Working Group commissioned this data collection and analysis effort to better understand how Boston area lab buildings compare to each other and to lab buildings nationally.

The Higher Education Working Group is chaired by Harvard University and managed by the Harvard University Office for Sustainability.

Acknowledgment

Support for this report is provided by the Boston-based Barr Foundation as part of its Climate Program and efforts to advance clean energy in the region.

Boston Area Laboratory Energy Benchmarking Study
Analysis Report: 2014 Data

Executive Summary

This report presents a new benchmarking dataset of 121 laboratory buildings from the Boston area higher education sector, compiled by the Higher Education Working Group (HEWG) of the Boston Green Ribbon Commission (GRC).

The purpose of whole-building energy benchmarking is to determine the efficiency with which a building meets its *functional requirements* (e.g. building type, building location, operating hours). Benchmarking can be used to rate buildings' efficiency, to prioritize candidates for energy studies, or to set energy usage targets for new or existing buildings. With the advent of building energy disclosure ordinances like BERDO[1] in Boston and BEUDO[2] in Cambridge, benchmarking can also provide much-needed context for energy data released publicly.

Laboratory building energy usage is higher than for most other types of buildings and is also highly variable between facilities. Without context, lab energy consumption can appear egregious. Comparing and contextualizing lab energy use is challenging because of the diverse and often energy-intensive functional requirements of lab buildings. The current set of energy benchmarking resources does not provide an equitable way to compare the energy consumption of any given lab with a peer group of similar buildings.

The EPA does not currently provide an ENERGY STAR® rating for lab buildings, and widely used national energy usage datasets such as the CBECS[3] sample contain very limited lab building data. The largest database of lab energy usage is the Labs21 Benchmarking Tool[4], which is home to a valuable searchable dataset of 639 buildings as of August 2016 (including 183 in Boston's Climate Zone 5A). While the Labs21 sample is the "gold standard" of lab benchmarking, it displays evidence of data quality issues; the scatter between data points is currently too high to allow development of a lab energy ranking.

The goal of the GRC study was to construct a new lab building benchmarking dataset comprised of Boston-area higher-education labs, with data quality exceeding that of any other sample. With a high-quality dataset, lab energy consumption can be contextualized and potentially ranked. This rich new dataset, which contains energy usage data for calendar year 2014 along with building properties and operational parameters, contains higher quality and more detailed data than any other known lab benchmarking dataset.

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[1] Building Energy Reporting and Disclosure Ordinance
[2] Building Energy Use Disclosure Ordinance
[3] Commercial Buildings Energy Consumption Survey, http://www.eia.gov/consumption/commercial/
[4] http://labs21benchmarking.lbl.gov/

Overall, Boston-area higher-ed lab building energy usage is consistent with that of labs as a whole nationwide. The average source energy use intensity of the GRC sample is 580 kBtu/sf/yr, compared with 602 kBtu/sf/yr across Boston's Climate Zone 5A and 630 kBtu/sf/yr nationwide. This report also documents energy usage patterns found for different types of lab buildings in the dataset.

The data were also analyzed to assess the potential for a lab building energy score based on a multivariate linear regression fit (akin to an ENERGY STAR® ranking). For chemistry and biology/biochemistry labs there is promise for an equitable ranking scheme; however, it appears that this approach is less suitable for buildings classified as physics/engineering. Further investigation and development is required before any rankings can be made public.

Whole-building energy benchmarking is necessarily a high-level, "soft-focus" activity which is best used to prioritize attention within a portfolio of buildings or to catalyze discussion on the energy consumption patterns of a particular facility. Any ranking derived from benchmarking data must be used with caution; it is inevitable that critical functional requirements of some buildings will not be taken into account in any given ranking system. It is not practical to collect data on every piece of specialty lab equipment, or on the space temperature tolerance of every room, in a large sample of buildings.

Promising next steps include:

- Incorporating other labs from the Boston area into the dataset, e.g. biotech and pharmaceutical labs. Essentially the same survey questions could be used; it is expected that this could double the number of buildings in the sample.
- Incorporating a further year of utility data. Examining the differences between 2014 and 2015 data will help to identify data issues and will allow assessment of the degree to which energy rankings depend on the year of data chosen.
- Investigating other functional requirements, e.g. density of research activities. This may require communication with space planning personnel.
- Providing individual institutions with energy reports on their buildings
- Submitting the data to the Labs21 database as a resource for the industry as a whole. Note that online searchable data are anonymized.
- Revisiting the energy score outliers and investigating the reasons for their apparently anomalous energy consumption levels.
- Revisiting missing or misleading building data to increase the richness of the dataset.
- Extending data collection efforts to include annual facility water usage.

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Acknowledgements

This report was prepared by kW Engineering on behalf of the Higher Education Working Group of the Boston Green Ribbon Commission. kW and the GRC wish to thank all participating facilities for collecting the data presented here and for providing valuable feedback in all phases of the work.

1. Introduction

The purpose of whole-building energy benchmarking is to determine the efficiency with which a building meets its *functional requirements* (e.g. building type, building location, operating hours). Benchmarking can be used to rate buildings' efficiency, to prioritize candidates for energy studies, or to set energy usage targets for new or existing buildings. With the advent of building energy disclosure ordinances like BERDO[5] in Boston and BEUDO[6] in Cambridge, benchmarking can also provide much-needed context for energy data released publicly.

Labs present a benchmarking challenge for several reasons, not least that the functional requirements of lab buildings are highly varied and unique to an extent not seen in most other building types. Spaces classified as laboratories include a large variety of usage types, e.g. tissue culture rooms, laser labs, clean rooms, machine shops, vivarium surgical suites, organic chemistry labs, freezer farms, and bio-safety level 3 suites. Ventilation requirements and space temperature and humidity requirements vary widely between different lab types, and the equipment installed in lab spaces ranges from benchtop magnetic stirrers to NMR machines. Benchmarking data collection must be designed to capture the essence of the specific energy-driving services that lab buildings provide to their occupants.

The EPA does not currently provide an ENERGY STAR® rating for lab buildings, and widely used national energy usage datasets such as the CBECS[7] sample contain very limited lab building data. The largest database of lab energy usage, and the only tool to provide lab-specific data collection and filtering, is the Labs21 Benchmarking Tool[8], which is home to a valuable searchable dataset of 639 buildings as of August 2016 (including 183 in Boston's Climate Zone 5A). While the Labs21 sample is the "gold standard" of lab benchmarking, it displays evidence of data quality issues; the scatter between data points is too high to allow development of a lab energy ranking.

The goal of the GRC study was to construct a new lab building benchmarking dataset comprised of Boston-area higher-education labs, with data quality exceeding that of any other sample. With a high-quality dataset, lab energy consumption can be contextualized and potentially ranked. Whole-building benchmarking is by nature and by necessity a "soft-focus" activity, but the availability of a uniform, consistent dataset is expected to greatly enhance the opportunity to develop a representative score.

Data quality enhancements were achieved in this study by specifically addressing the issues plaguing other datasets, such as weather variations and inconsistent interpretation of data requests; the data collection process is described in detail in Section 2 of this report. Demographics of the GRC sample are presented in Section 3, and energy usage results are provided in Section 4. Section 5 describes the analysis carried out to determine the potential for a lab building energy ranking akin to an ENERGY STAR® score. Conclusions and recommended next steps are discussed in Section 6.

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[5] Building Energy Reporting and Disclosure Ordinance
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[7] Commercial Buildings Energy Consumption Survey, http://www.eia.gov/consumption/commercial/
[8] http://labs21benchmarking.lbl.gov/

2. Approach

Data Collection

The data requested for each building fall into four main categories:

a. **Whole-building annual energy usage:** energy consumed (from all sources) in calendar year 2014. These values are used to calculate total annual energy usage and annual energy use intensity (EUI) values for each building.

b. **Building functional requirements:** these are the metrics on which buildings are compared, and include total building area, total lab area, number of fume hoods, and predominant lab type (biology/biochem, chemistry, physics/engineering, and other[9]). Functional requirements are the services that a building must provide to its occupants. Importantly, these are distinct from the design features or operational parameters employed to meet these requirements. When ranking building energy usage, it is appropriate to compare buildings with similar functional requirements.[10]

c. **Building design and operational parameters:** these include properties of the buildings that are expected to influence energy consumption but which are not necessarily needed to meet functional requirements. Examples include HVAC system type (e.g. variable air volume with reheat), HVAC control type (e.g. pneumatic), and the use of night airflow setback in labs. While these parameters are not used to select peer buildings for comparison, they were collected in order to assess the effectiveness of any candidate ranking system developed as part of this study: buildings with more energy-efficient features might be presumed to typically consume less energy than nominally similar buildings without these features.

d. **Perceived energy efficiency:** respondents were asked to rank the buildings in terms of efficiency of original design and efficiency of current operation. The answers to these questions can also be used to assess any potential ranking system, or to determine whether any correlation exists between a building's reputation and its actual energy consumption.

The data points requested for each building are shown in Table 1 below. Thirty-four data values were requested for each facility; 18 of these were mandatory. Facility representatives were invited to participate in conference calls addressing the data requests in detail; facility staff questions were also answered on these calls.

[9] These lab type classifications refer to the predominant type of science that is performed in each facility.
[10] If a benchmarking analysis were to be used to identify operational inefficiencies in buildings, then the metric for comparison would include design parameters of the building, e.g. presence of exhaust air heat recovery or exhaust fan system control type. This is not the type of benchmarking addressed here.

Table 1: Data Requested for Each Building

Basic Info	CY 2014 Energy Usage	Building Breakdown	HVAC Systems	Occupancy	High-Intensity Spaces	Perceptions
Institution	**Electricity**	***Gross building area***	***# fume hoods***	***Typical occupied hours***	*Freezer farms*	**Efficient design?**
Building name	**Chilled water**	***Predominant non-lab space type***	FH control type	Partial occupancy in 2014?	*Data centers*	**Efficient operation?**
City	**Natural gas**	***Lab type***	Lab HVAC system type		*Clean rooms*	
Year built	**Steam or HW**	***Lab purpose***	HVAC control type			
	Metered or modeled	***Total lab area***	*Design min ACH in labs*			
		Total vivarium area	Night airflow setback in labs?			
			24/7 HVAC operation?			
			100% outside air?			
			Exhaust air heat recovery?			

Legend:

Mandatory data requests in **bold**.

Standard Labs21 Benchmarking Tool data points in green.

Functional requirements in *italics*.

The data collection methods were constructed strategically to reduce or eliminate the sources of data scatter and pollution that plague other studies. These strategies include collection of data for a single calendar year, to reduce data scatter due to weather variations. While data can be corrected to some extent for weather variations, the process is inexact (and ideally uses monthly usage data or data covering a number of years). The ranges of data collection year for the Labs21 national sample and for the GRC sample are illustrated in Figure 1 below.

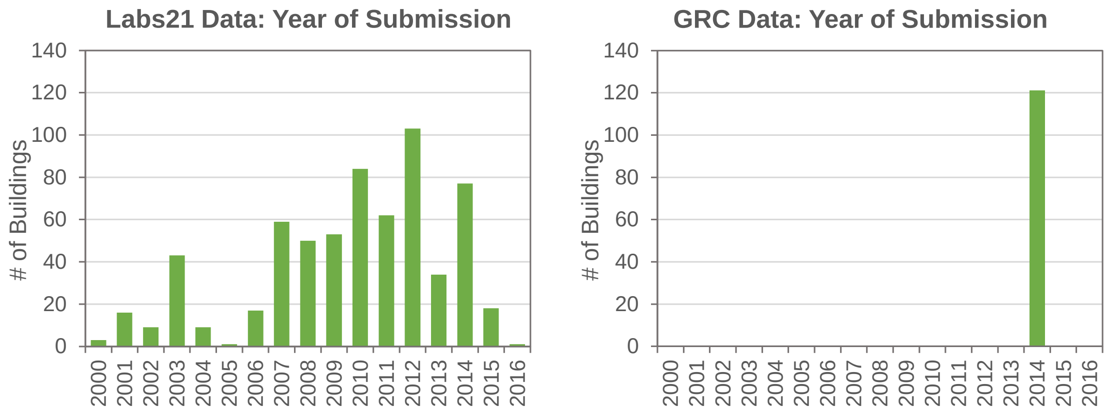

Figure 1: Year of Data Submission for Labs21 Dataset as of 2016 (Left) and GRC 2014 Sample (Right)

Similarly, and in contrast to the samples used for ENERGY STAR® and in the Labs21 dataset, the GRC sample by definition only includes buildings from the same geographic region. The spread of locations contained in the Labs21 and GRC datasets is illustrated in Figure 2 below.

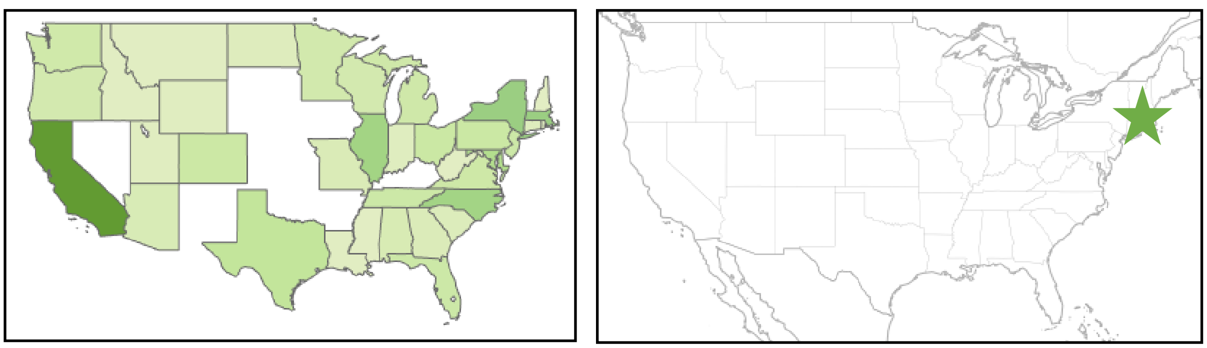

Figure 2: Labs21 Dataset Locations as of 2015 (Left); GRC Sample Location (Right)

Other strategies employed included working with facilities staff to ensure consistent definitions of lab area and qualifying space types.

Data were collected in an Excel spreadsheet. Wherever possible, non-numerical fields were provided with drop-down menus for selection. “Other” responses were encouraged only where a reasonable drop-down option was not provided. This helps to ensure that all data can be compared on an equal footing.

Basic quality control of data was performed upon receipt. Missing or clearly anomalous points were flagged; facilities staff were contacted with questions and data were amended or removed from the sample as appropriate. In this way the most egregious points were removed from the sample. However, it must be stressed that no independent checks were made on lab areas, on utility usage (beyond flagging outliers), or on other building properties. Data submitted by facilities staff were assumed to be predominantly correct. This is a significant assumption and undoubtedly some inaccurate data still persist in the sample. Additional discussion on this issue is provided in the regression analysis section of this report.

The project’s data collection strategies are summarized in Table 2 below.

Table 2: Summary of Problems with Standard Benchmarking Approaches, with Solutions Implemented in this Study

Problem with Standard Approaches	Solution Implemented
Poor data quality due to inconsistent interpretation of instructions, leading to uncertainties in conclusions and correlations.	Overview conference calls and email support for facilities staff. Refined list of data requests. Analysis by a single engineering firm with in-depth lab and benchmarking experience.
No energy ranking available from Labs21 tool, due in part to significant data scatter.	Reduce scatter by improving data quality. Understand origin of scatter by following up on outliers. Assess potential for Boston area lab energy score.
Varied central plant (district) energy use makes site energy comparisons inappropriate.	Treat campus central plant energy use consistently and transparently; use source energy, calculated using standard factors.
No weather normalization in Labs21 Tool.	Use dataset from small geographic region and consistent time period, avoiding the need for weather normalization.
Labs21 Tool does not collect data on function of non-lab portions of buildings, potentially contributing to data scatter.	Collect list of all building functions (e.g. office, data center, garage) to allow follow-up assessment.
Data collection for a large sample of buildings can be time-consuming and expensive.	Leverage familiarity of facilities staff with buildings on their campuses. Provide training to allow staff to collect data (and to do so independently in future years as part of follow-up studies).
Collection of a large number of data points per building is onerous and prone to error.	Streamline list of data points to include only the most relevant and significant items. Avoid requesting data (e.g. end-use submeter data or system-level metrics) not readily available for the majority of buildings.

Weather Analysis

All utility data was requested for calendar year 2014, with a goal of eliminating data scatter due to variation of weather conditions between records. Weather variations affect national and multi-year datasets such as those used to construct ENERGY STAR® rankings and the Labs21 Benchmarking dataset.

While envelope loads tend to be less significant for lab buildings than for many other building types, labs' 100% outside air requirements mean that weather is still a critical factor in determining building loads. Lab building energy consumption may therefore vary significantly between years with different weather patterns.

Based on the data presented in Figure 3 below, it can be concluded that 2014 was close to a typical weather year for Boston. The annual total cooling degree days (base 65°F) varied by 5% from Typical Meteorological Year (TMY3) values, while total heating degree days (base 65°F) varied by 1%.

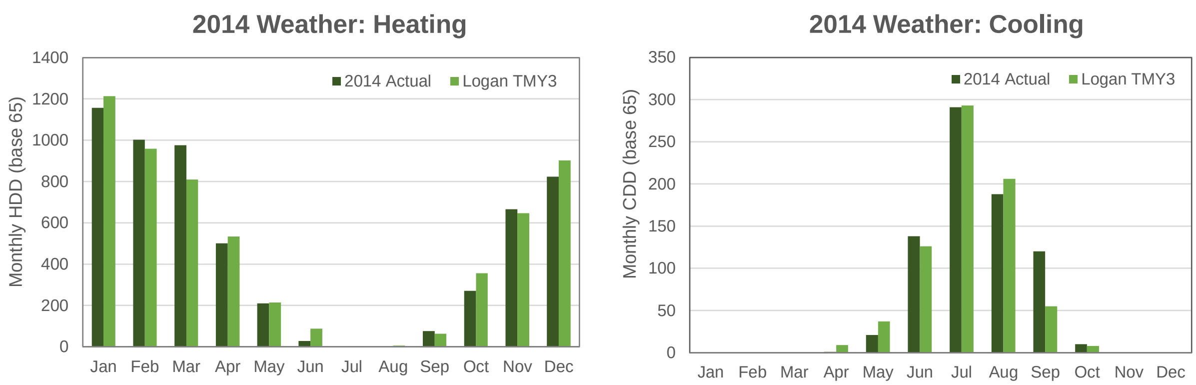

Figure 3: Comparison of 2014 Boston Weather Data with Typical Meteorological Year (TMY3) Data

The reported 2014 energy consumption levels of the buildings can therefore be assumed to be fairly representative of a "typical" year.[11]

[11] Adding a second year (2015) of data to the dataset would be a valuable way to assess the dependence of comparisons with national data and of derived energy scores on weather variations.

Energy Sources and Source Energy

To compare the energy usage of different buildings, it is helpful to combine energy usage data from different sources (e.g. electricity, district chilled water, natural gas) into a single building energy consumption metric. A number of metrics are in common use: *site energy* includes only the energy consumed at the building itself; *source energy* also includes the energy used to generate and transmit the energy used on site; and *CO_2 emissions* and *energy cost*, both typically closely related to source energy consumption, are also used frequently.

Many of the GRC sample buildings are connected to campus central plants, rendering site energy unsuitable as a metric for comparison. Where energy sources differ between buildings – and in particular where some (but not all) receive district chilled water – site energy usage is distorted because the energy usage of some buildings includes the energy used to generate the utilities while for other buildings it does not. Note that the published BERDO analysis, where the sample includes a smaller proportion of buildings connected to district energy plants, chiefly uses site energy.

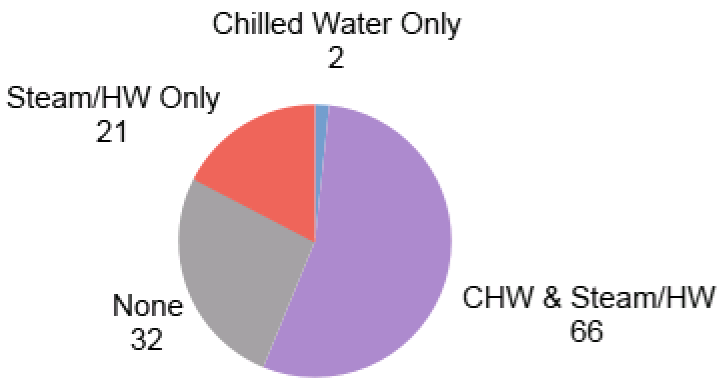

Figure 4: Central Plant Utility Source Breakdown for the GRC Sample. (Numbers shown on the chart correspond to the total number of buildings in each category.)

For this study, energy data are presented primarily in terms of *annual source energy* usage and annual *source energy intensity* (source energy usage per unit area). The use of source energy as a basis for comparison greatly reduces the distortions introduced by the diversity of energy sources within the sample, and provides a metric more closely tied to buildings' climate impact.

Standard ENERGY STAR® Portfolio Manager site-to-source conversion factors for electricity and district energy were used to convert building metered energy usage to source energy usage. This is necessarily an approximate approach: it does not take into account differing efficiency of on-site primary equipment and central cogeneration facilities, and the standard conversion factors may not be truly representative of the electricity generation mix in Massachusetts. However, the use of standard conversion factors allows comparison between buildings – the fundamental goal of this exercise – independent of the details of central plant efficiency.

3. Results: Demographics

All data were collected by the GRC between February and June 2016. Seven institutions submitted energy usage and building data for a total of 121 lab buildings (14.7 million sf). The GRC dataset contains between one and 43 buildings per institution.

The breakdown of buildings by predominant lab type is shown in Figure 5 below. The sample is dominated by biology/biochemistry and physics/engineering lab types. “Other” reported lab types include manufacturing, pharmacy/health science, medical, dental, and vivarium.

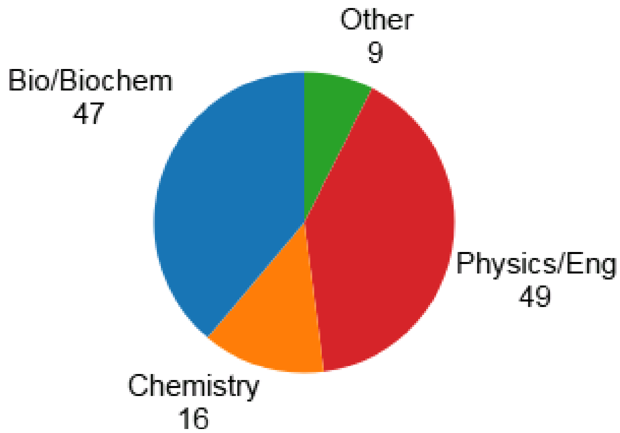

Figure 5: Distribution of Predominant Lab Type in the GRC Sample. (Numbers shown on the chart correspond to the total number of buildings in each category.)

The breakdown of buildings by area is shown in Figure 6 below. The color scheme used in the figure (and in many others throughout this report) is the same as that used in Figure 5 above. Approximately 22% of the buildings in the GRC sample are smaller than the 2014 BERDO cutoff (50,000 sf) for mandatory reporting of energy data.

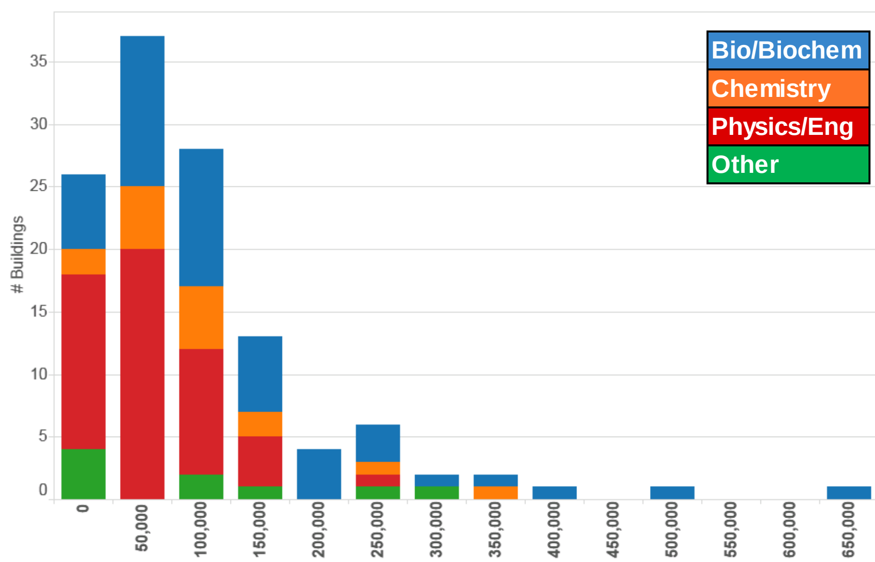

Figure 6: Distribution of Building Area (by Lab Type) in the GRC Sample

The percentage of lab space by area ranges from less than the nominal minimum used for the study (15%) up to more than 90% for some highly specialized facilities. The median percentage lab area is 35%.

Figure 7 displays the distribution of decade of construction. Large numbers of higher-ed lab buildings were built in the 1960s-70s and since 1990. Biology/biochem laboratories have dominated new construction since the 1990s. The GRC sample contains a larger proportion of pre-1920 construction than the BERDO sample (which includes many building types).

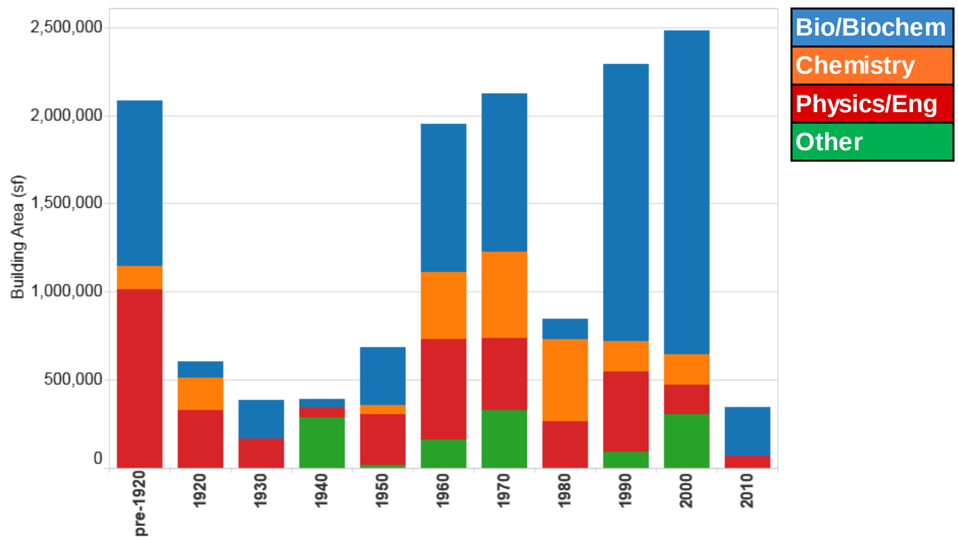

Figure 7: Distribution of Decade Built and Lab Type in the GRC Sample

Table 3 summarizes the demographics of the GRC sample. For 82 of the 121 submitted buildings, the energy data were based on direct metering of utility consumption at the building level. For most of the remaining buildings, submitted data were taken from accounting allocations used in the absence of building-level meters; a few other buildings were missing some utility usage data. Buildings with missing data are excluded from the analysis presented in the rest of this report (but were included in the demographic charts above). Data from buildings with metering allocations are included in most analyses (and are shown as square data points where applicable) but were excluded from the regression analysis, where uncertain data may artificially increase scatter.

Table 3: Summary of GRC Sample Demographics

	Fully Metered			All Submissions		
	# of Buildings	Total bldg area (sf)	Median Lab %	# of Buildings	Total bldg area (sf)	Median Lab %
Bio/Biochem	41	6,730,965	46%	47	7,527,513	39%
Chemistry	13	1,782,817	46%	16	2,050,072	46%
Physics/Eng	21	1,980,529	27%	49	3,960,233	27%
Other	7	1,051,575	27%	9	1,195,059	28%
Totals	82	11,545,886	38%	121	14,732,877	35%

4. Results: Energy Usage

The total source energy usage for the GRC sample buildings (those with full metering or with energy use allocations) is illustrated in Figure 8 below. The sample consumes a total of 6.6 billion kBtu/yr, which for reference is equivalent to 10% of the energy used by all buildings in Boston[12], or 45 million sf of typical office space[13]. Of the sample of 116 buildings, 26 are responsible for approximately half of the total source energy consumption.

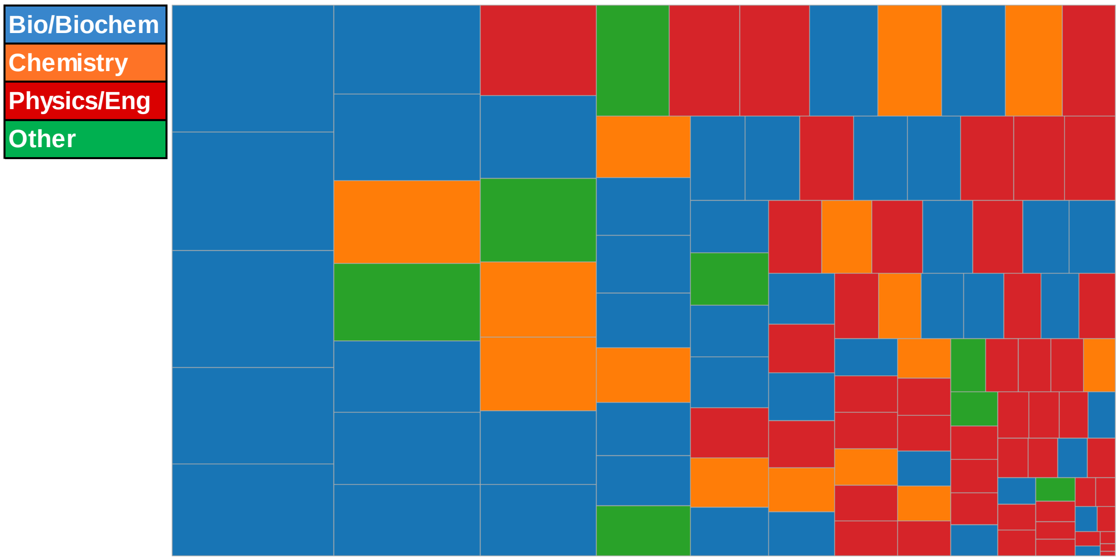

Figure 8: Tree Diagram Showing Source Energy Consumption for Each Building. (Size of rectangle reflects total source energy consumption of building.)

The energy usage intensity data are summarized in Table 4 below. The average source energy use intensity of the sample is 580 kBtu/sf/yr. The spread is significant: the standard deviation of source energy intensity is 260 kBtu/sf/yr. The highest EUI is 1,566 kBtu/sf/yr, and the lowest is 127 kBtu/sf/yr. For comparison, the average source energy intensity reported in the Labs21 data for climate zone 5A is very similar at 602 kBtu/sf/yr (with min and max of 124 and 1,916 kBtu/sf/yr) respectively).

Table 4: Energy Use Summary for the GRC Sample (Fully Metered Data Only)

	# of Buildings	Avg. Source EUI (kBtu/sf/yr)	Stdev of Source EUI (kBtu/sf/yr)	Avg. Site EUI (kBtu/sf/yr)
Bio/Biochem	41	592	229	317
Chemistry	13	663	179	369
Physics/Eng	21	486	335	253
Other	7	644	272	362
All	**82**	**580**	**260**	**312**

[12] From 2014 BERDO report data (p14)
[13] Based on ENERGY STAR® Portfolio Manager median national office building source energy intensity of 148 kBtu/sf/yr.

Physics/engineering lab buildings have lower average EUI and show greater variability in energy intensity, likely reflecting the greater variety of space types covered by this definition than for biology/biochem or chemistry labs. The physics and engineering category encompasses spaces ranging from machine shops to clean rooms and laser labs; the variation in energy intensity between buildings in this category is expected to be large.

Figure 9 illustrates the source EUI distribution of the GRC sample, including a breakdown by lab type.

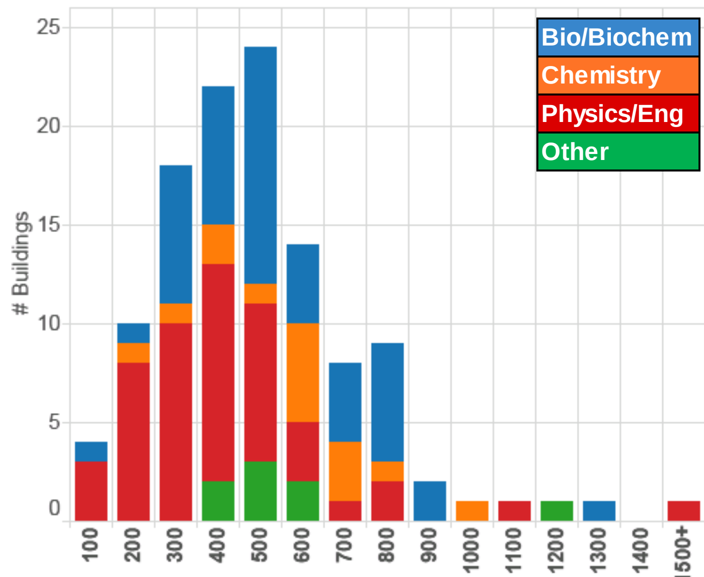

Figure 9: Source EUI Distribution (kBtu/sf/yr) for the GRC Sample (Fully Metered and Allocated)

Figure 10 displays the median energy intensity as a function of decade of construction. Similar to the BERDO findings for all building types, older buildings are found to be somewhat less energy intensive than newer ones. Unlike the BERDO findings, the post-1980 buildings in the sample do not appear to consume significantly less energy than those built in the 1960s or 70s.

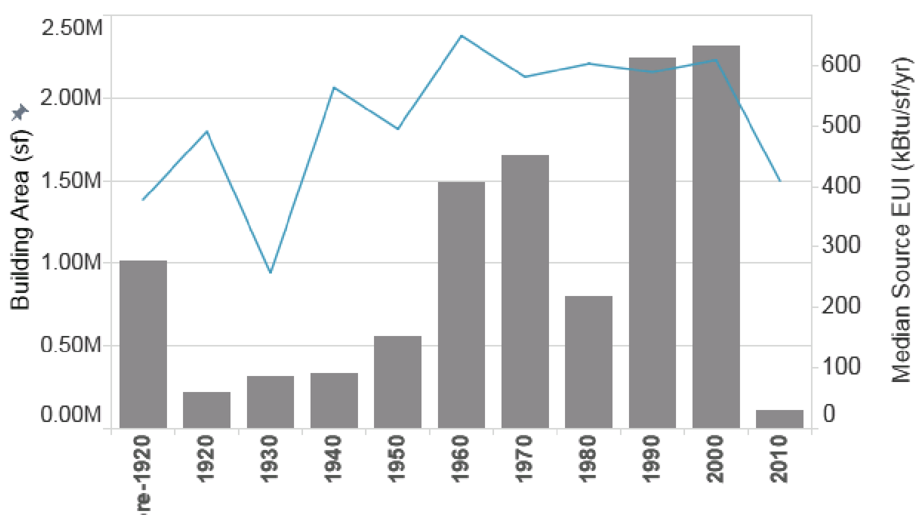

Figure 10: Building Area (Grey Columns) and Median Source EUI (Blue Line) by Decade Built for the GRC Sample (Fully Metered Data Only)

To allow direct comparison, the lab type classifications from the Labs21 Tool were reallocated to more closely match the categories used in this study. For each lab type, the energy usage level is similar for GRC and Labs21 samples. Note that Climate Zone 5A spans the Chicago area as well as the Boston area, and that the Labs21 sample contains (anonymized) buildings from all types of lab facilities, not just the higher education sector. It is therefore unlikely that there is significant overlap between the buildings contained in each sample.

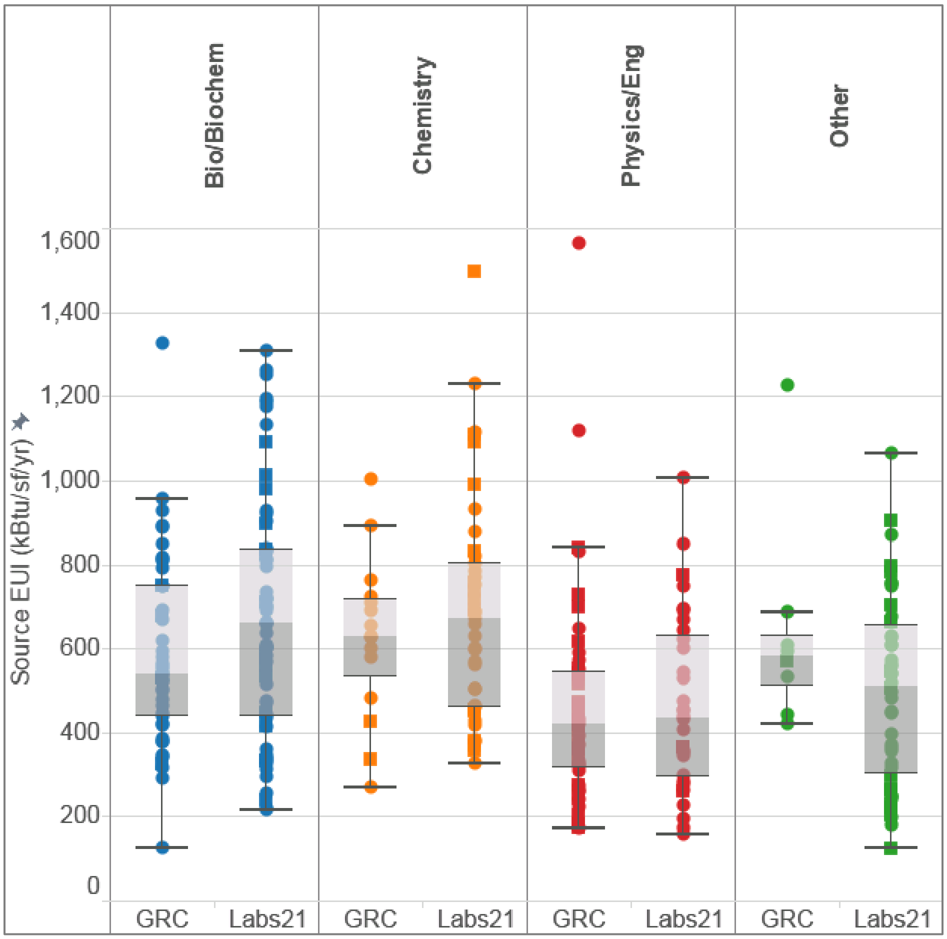

Figure 11: Source EUI Distribution by Lab Type for GRC and Labs21 (Climate Zone 5A) Samples. Square data points indicate allocated utility data; circles represent fully metered data. In this and all other box and whisker plots in this report, the light grey box extends between the median and the upper quartile of each dataset; the dark grey box extends from the median to the lower quartile. The "whiskers" (vertical lines) extend to those data points within 1.5 times the interquartile range of the outer edge of the grey box.

From the figure above, it can be concluded that Boston-area higher-education lab buildings have comparable energy consumption to those in Climate Zone 5A as a whole.

5. Results: Analysis

Energy Score Development: Motivation

A primary purpose of energy benchmarking is to enable comparison of energy consumption between buildings; common examples include ENERGY STAR® rankings and LEED EBOM certification. The public release of energy usage data inevitably leads to comparisons between facilities. When ranking buildings, it is critical to develop an equitable basis for comparison. This basis typically consists of a subset of the building's functional requirements, i.e. the services it must provide (and the location in which it resides).

As discussed in the introduction, laboratory buildings have diverse functional requirements, many with significant energy impacts. The desire to collect exhaustive data on these requirements must be balanced against the need to receive accurate data within a reasonable timeframe.

The analysis presented here represents a preliminary effort to construct an energy ranking for Boston-area lab buildings using the new GRC dataset. While the potential for a ranking system is promising, it is important to note that no buildings should yet be ranked publicly using this preliminary system and that the tentative rankings derived here will not be released.

Similar to the approach used by ENERGY STAR®, the GRC analysis involves a multivariate linear regression. The regression analysis is used to establish correlations between selected functional requirements and building energy intensity. The energy consumption of individual buildings can then be compared to the predicted "typical" level of consumption (calculated using the regression parameters) for a building with the same functional requirements. Rankings obtained through this type of analysis are relative to the building population as a whole (as distinct from "absolute" efficiency rankings).

Prior attempts have been made to perform this type of analysis for laboratory facilities, including a 2010 analysis using the Labs21 dataset (when the database contained significantly fewer facilities)[14]; a more recent analysis by the I^{2}SL Lab Benchmarking Working Group[15] showed that data quality issues may limit the utility of a regression analysis of the current (much larger) Labs21 dataset. Additionally, the EPA is in the process of developing an ENERGY STAR® ranking scheme for pharmaceutical research laboratories.

Regression Analysis: Candidate Variables

The first step in the regression analysis is selection of the functional requirements likely to have the largest impact on building energy use intensity. The most significant parameter is expected to be the fraction of the building's area occupied by laboratories: the lab portions of a building typically have higher ventilation rates, more stringent control of space conditions, potentially longer hours of operation, and higher equipment load intensities than the other spaces in the building. Searching for a correlation between **percentage lab area** and EUI is therefore a useful first step. Figure 12 below compares this relationship for the GRC sample, for climate zone 5A

[14] Mathew, P. et al, 2010 Advanced Benchmarking for Complex Building Types: Laboratories as an Exemplar, 2010 ACEEE Summary Study on Energy Effiicency in Buildings
[15] http://www.i2sl.org/working/benchmarking.html

buildings from the Labs21 dataset, and for the full national Labs21 dataset for the four categories of lab type used in this study.[16]

All three datasets show the expected correlation between fractional lab area and EUI, but the GRC dataset shows significantly less scatter than the others. This promising result is most likely due to the geographic and temporal restrictions placed on the dataset, and on the careful data collection methods. By removing a large part of the scatter not associated with building efficiency, correlations derived from the data will have greater predictive power and will be more useful. The quality of the GRC data sample is higher than the existing gold standard data for lab benchmarking.

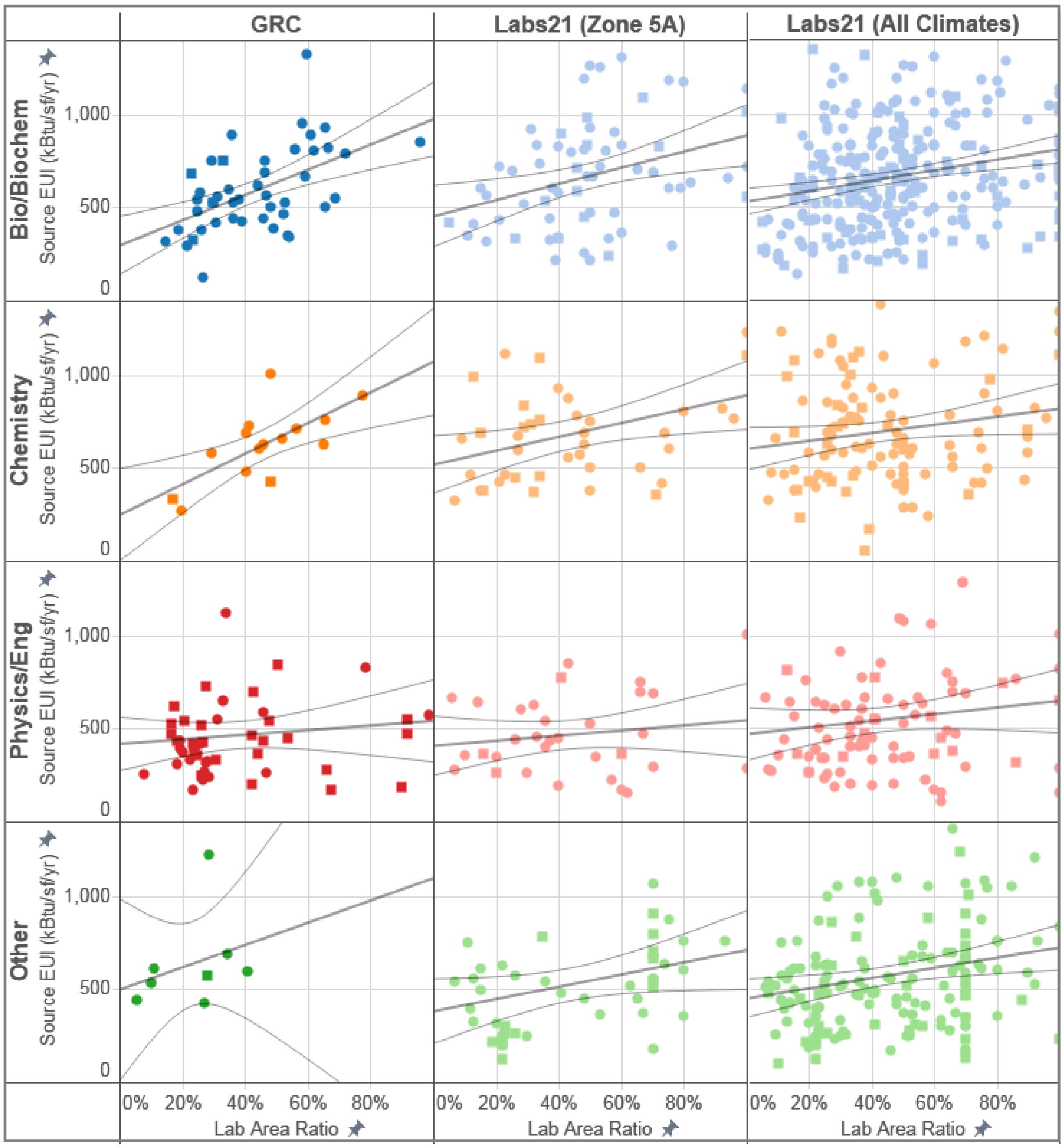

Figure 12: Source EUI by Lab Type vs. Lab Area Fraction for the GRC sample (left), the Labs21 Climate Zone 5A Sample (middle), and the Full Labs21 National Sample (right)

[16] The Labs21 lab type categories were reassigned to match those used here.

As noted previously, the scatter seen in the physics/engineering buildings is larger than for biology/biochem and chemistry lab types. Additionally, the energy usage appears to be less strongly dependent on the percentage lab area; this may be a result of energy usage for physics and engineering buildings being more typically driven by a few pieces of equipment or high-intensity spaces rather than by a typical level of consumption of the building's lab spaces.

Other candidate variables: Because equipment and ventilation requirements vary for labs housing different types of research, lab type (bio/biochem, chemistry, physics/engineering) is also expected to have a significant impact on energy intensity.

Other important energy-driving factors might include the density of fume hoods in the buildings: hood exhaust, at high fume hood densities, drives space exhaust and make-up air requirements and therefore impacts energy usage. For typical fume hood and overall lab airflow rates, hoods will become airflow drivers above densities of approximately one hood per 1,000 sf of lab space. Figure 13 below shows a scatter plot of source EUI versus fume hood density (number of fume hoods per total lab[17] square footage). Some dependence is seen, suggesting that this parameter should be included in the regression analysis.

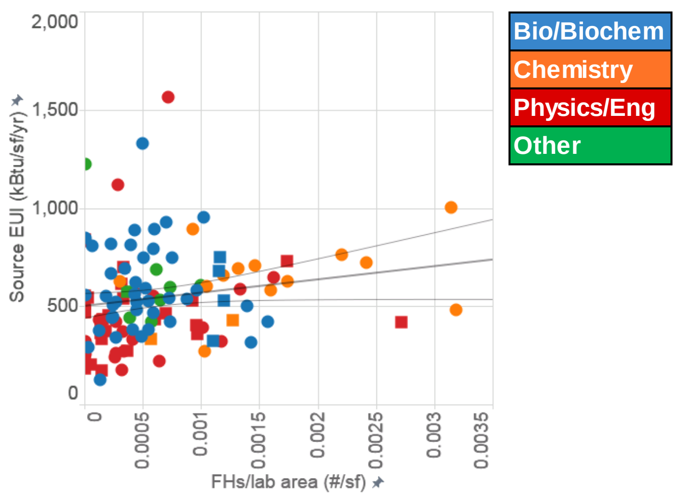

Figure 13: Source EUI vs. Number of Fume Hoods Per Unit Lab Area for the GRC Sample

Additionally, weekly hours of occupancy were included as a candidate variable in the regression analysis. The drop-down menu responses on building occupancy provided by facilities staff were converted to nominal hours of occupancy for use in the regression analysis. This variable is not expected to have a strong impact on lab energy use intensity, because true building occupancy hours are difficult to define when many experiments run 24/7, HVAC systems operate continuously, and some level of occupancy is common at all hours.

Note that building age was not used as a regression variable here: year of construction is not considered to be a functional requirement for the purposes of this study. Further, if age were indeed to be given a "free pass," complications would arise regarding building renovations.

[17] Lab area was used in place of total building area in order to avoid degeneracy with the overall lab percentage area variable used in the regression analysis.

Regression Analysis: Initial

An initial regression analysis was performed using the candidate variables described above and the sample of buildings with fully metered data (excluding labs classified as “other” types); 75 buildings were included in the analysis.

The analysis returned a multilinear fit to the data. The percentage residual, defined as (actual EUI – predicted EUI)/(predicted EUI), represents the amount by which a building’s actual energy consumption differs from that predicted by the regression equation. Figure 14 shows the distribution of the percentage residuals for the three lab types included in the initial regression analysis. For biology and chemistry buildings, approximately 2/3 of the buildings show energy use within ±25% of predictions; there appears to be potential for a ranking system for these buildings. The distribution of residuals was far broader for physics/engineering buildings: the regression equation does not appear to be a good predictor of energy usage. This was anticipated above, and refinements to the functional requirements used for these buildings could be the subject of future work. For the purposes of the current study, the regression analysis was repeated with the physics/engineering buildings removed.

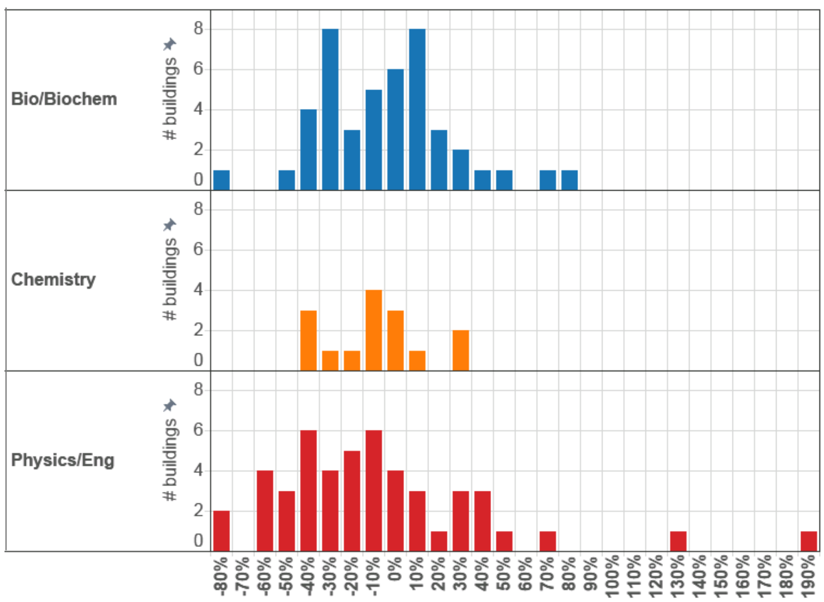

Figure 14: Distribution of Initial Regression Residuals for Bio/Biochem, Chemistry, and Physics/Eng Labs from the GRC Sample

It is important to note that, while lower residuals (higher R^2) are desirable from an energy prediction standpoint, it is not expected or desired that the correlation between functional requirements and energy intensity will be 100% predictive: the residuals described above represent a combination of several effects: functional requirements not included in the analysis, data inaccuracies (if present), and – importantly – *differences in building energy efficiency*, i.e. the signal that the analysis is designed to find.

Regression Analysis: Bio/Biochem and Chemistry Buildings Only

The regression analysis was repeated for just the buildings classified as bio/biochem or chemistry with fully metered utility data (54 buildings total). The linear regression analysis was based on the following variables:

- % lab area (bio/biochem buildings)
- % lab area (chemistry buildings)
- Fume hood density (# hoods/lab sf)
- Operating hours per week.

The derived regression coefficients and their standard deviations are shown in the table below.

Table 5: Results of Regression Analysis for Bio/Biochem and Chemistry Labs Only

	Coefficient	Stdev	Significant?
% lab area (bio)	807	157	Yes
% lab area (chem)	800	190	Yes
Weekly operating hours	-1.8	1.4	No
Fume hoods/lab sf	45,494	48,900	No
Constant	380	159	Yes

Fume hood density and weekly operating hours were found to have no statistical significance (the coefficient value divided by its standard deviation does not significantly exceed unity[18]). These variables could be removed from future iterations of the regression analysis. Note that their presence in the regression equation does not prevent our initial assessment of the tentative energy ranking system.

The R^2 for the regression was 38%, i.e. 38% of the source EUI variations between buildings are explained by the regression parameters used. This is similar to the findings of the 2010 ACEEE study using the Labs21 data (34%), but much higher than the value found in the I^2SL analysis of the current Labs21 dataset (11%).

Including building area as a determining factor, the **overall R^2 value is 79%**, i.e. 79% of the variation of source energy consumption between buildings is explained by the factors used in the regression analysis. The derived regression equation therefore has significant predictive power.

For comparison, the analysis used to set ENERGY STAR® rankings for office buildings[19] yields an R^2 of 33% for EUI and 79% for total source energy. For hospitals[20], these numbers are 24% and 88%. The GRC results here are therefore in line with the level of predictive power deemed acceptable by ENERGY STAR®. Note that some important differences exist between the analyses, e.g. ENERGY STAR® data include differences in weather between building sites.

[18] A typical threshold value used for this ratio (above which the variable is deemed a useful piece of the regression) is 2.4.
[19] ENERGY STAR Portfolio Manager Technical Reference: ENERGY STAR Score for Offices in the United States, November 2014.
[20] ENERGY STAR Portfolio Manager Technical Reference: ENERGY STAR Score for Hospitals in the United States, November 2014.

Energy Score Development: Test Scoring System

A tentative “energy score” for Boston-area bio/biochem and chemistry lab buildings was developed based on the regression analysis described above. The quartile ranking system is shown in Table 6 below. The buildings ranked as “most efficient” (Quartile 1) are those that fall further below the predicted energy usage than 75% of the original sample used to develop the ranking. If an ENERGY STAR®-like scheme were applied here, these buildings would receive ENERGY STAR® certification.

Table 6: Quartile Ranking System and Color Scheme

	Quartile	EUI Relative to Prediction
Most Efficient	1	>22% below predicted
	2	0-22% below predicted
	3	0-16% above predicted
Least Efficient	4	>16% above predicted

Energy Score Development: Outlier Analysis

As part of the validity checking process for any ranking system, it is important to examine those buildings which are assigned high and low scores in the proposed scheme. The five highest- and lowest-scoring bio/chem buildings in the sample were examined in this way.

Reported building properties, where provided, were divided between those that are commonly associated with high and low building energy consumption. These properties are shown in the tables below, along with decade of construction and any other comments.

Table 7: Properties of the Five Highest-Scoring ("Most Energy-Efficient") Buildings

#	Decade Built	High Energy Usage Markers	Low Energy Usage Markers	Comments
1	1940s	Mixture of HVAC control types; no setback	None of building is 100% outside air (OA); no systems operate 24/7; no high-intensity spaces	Unusual metering situation; exclude from sample in future analyses
2	1900s	No setback	Dedicated Outdoor Air System (DOAS) + Fan Coil Units (FCUs), no high intensity spaces; VAV fume hoods; exhaust heat recovery	
3	1900s	No setback	DOAS+FCUs, no high intensity spaces; VAV fume hoods; exhaust heat recovery	
4	1970s	CV fume hoods; no setback; mix of HVAC control types	Teaching labs; 100% OA only for labs; no high-intensity spaces	
5	1910s	10+ ACH; no setback; true 24/7 occupancy; mix of HVAC control types	VAVRH; no high-intensity spaces	

Table 8: Properties of the Five Lowest-Scoring ("Least Energy-Efficient") Buildings

#	Decade Built	High Energy Usage Markers	Low Energy Usage Markers	Comments
1	1950s	CV RH system	No high-intensity spaces	Electricity usage may be anomalously high
2	1990s	CV RH system; 8 ACH; large vivarium; many freezers; mixture of control types	None	System incorrectly reported as VAV RH
3	2000s	Operation noted to be inefficient	Exhaust heat recovery; 100% OA only for labs	Limited info provided
4	1950s	None	100% OA only for labs	Limited info provided
5	1960s	Non-manifolded exhaust fans	100% OA only for labs	Limited info provided

With the exception of buildings with unusual metering situations (especially the highest scoring building, which should be removed from the sample in future analyses), the reasons for high or low scores are not overwhelmingly apparent from an examination of this data. This does not necessarily mean that the approach is infeasible. As discussed below, a number of data submissions relating to HVAC system properties were missing or inaccurate. Second, a number of parameters that were not part of the original data request can have major impacts on the energy consumed by lab buildings. An excellent example is discharge air temperature strategy, which can have large impacts on heating and cooling energy usage. Other items not requested include details on process loads (e.g. chilled water or steam loads) and humidification systems, and an inventory of specialty spaces (beyond data centers, freezer farms, and clean rooms).

Further specific investigation of the outlier buildings is recommended in order to eliminate these sources of uncertainty.

Energy Score Development: Full Sample Analysis

If a ranking system is to be useful, buildings with more efficient design (or operation) should generally receive better energy scores than those with less efficient designs (or operation). The draft energy ranking scheme was tested by looking for correlations between energy score and building properties.

As might be anticipated from the results on building energy usage as a function of decade of construction (Figure 10), Figure 15 below shows that older lab buildings generally receive better scores than newer ones.

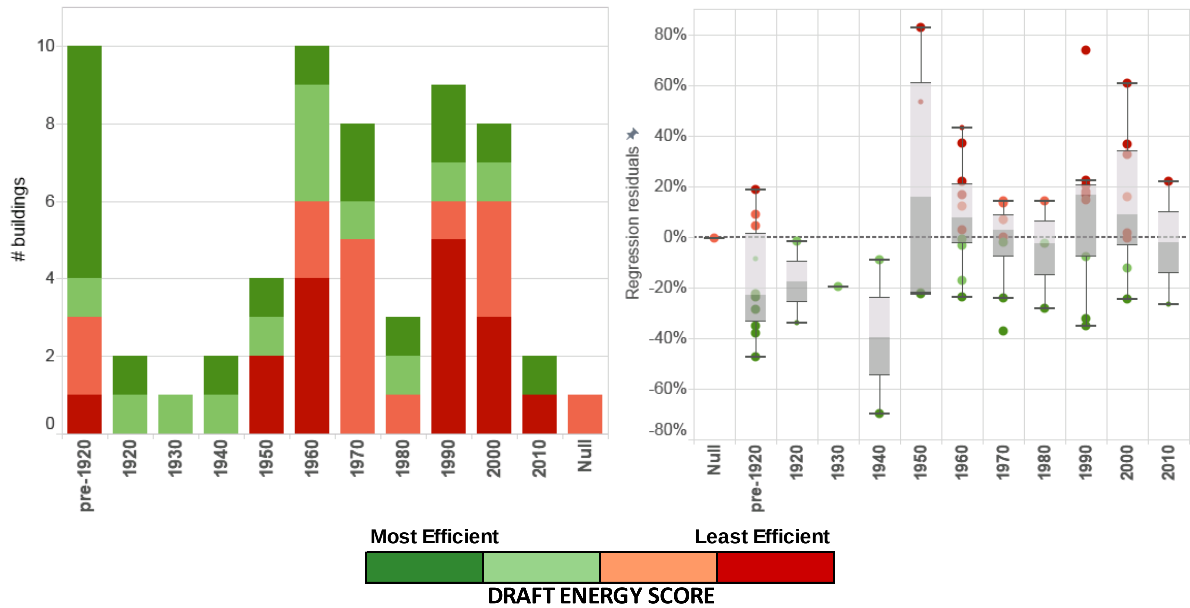

Figure 15: Energy Ranking by Decade of Construction (Note: Left and Right Figures Show Same Data). Colors of Columns and Data Points Represent Energy Rankings.

Figure 16 below shows the distribution of candidate energy scores as a function of three additional factors: HVAC system type; presence or absence of exhaust heat recovery; and lab purpose. Note that a lower position in the chart (green data points) indicates lower energy usage (relative to the regression prediction) and therefore a higher energy score.

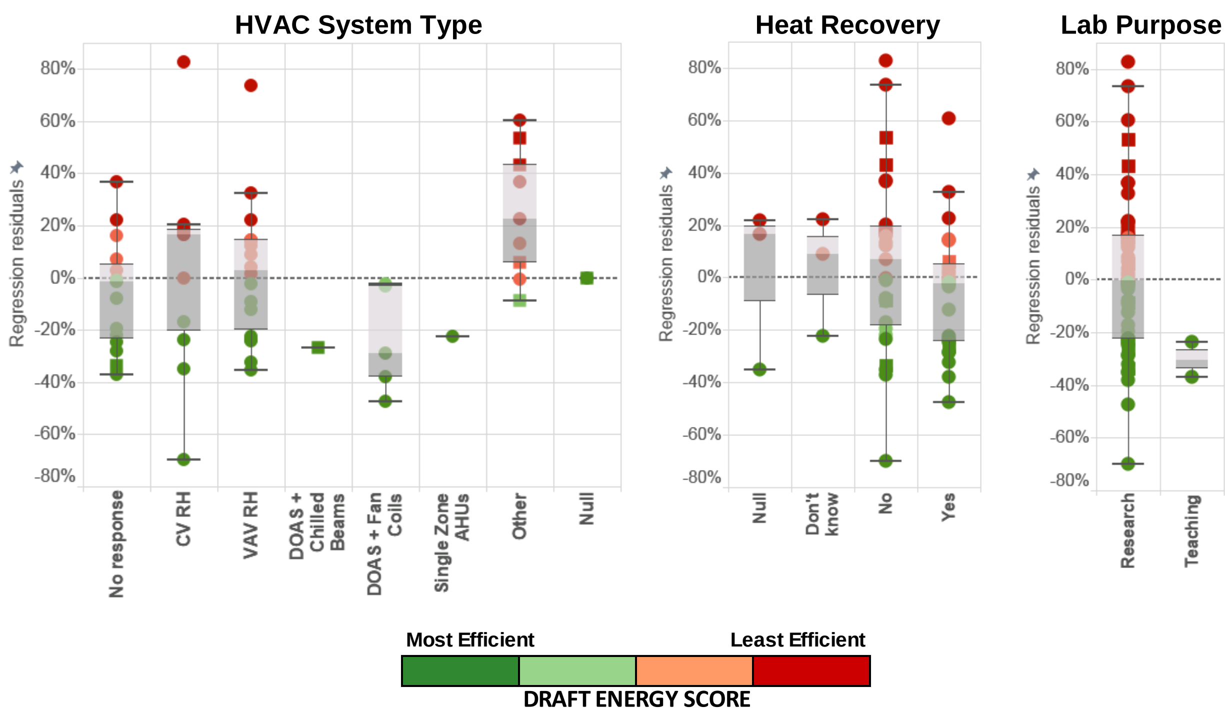

Figure 16: Residuals (Energy Score) for Bio/Biochem and Chemistry Buildings as a Function of HVAC System Type (Left), Presence of Exhaust Heat Recovery (Middle), and Lab Purpose (Right). Data Point Colors Represent Energy Rankings.

For the three building properties plotted above, the energy scores follow the expected pattern. While there is significant scatter, buildings with more efficient system types have higher energy scores: the median energy score of buildings with variable air volume (VAV) HVAC systems is higher than that of buildings with constant air volume (CV) systems; buildings with dedicated outside air systems receive higher scores than those served by other system types; and buildings with heat recovery systems, for given lab area fraction (and hood density and occupied hours) receive higher scores than those without heat recovery. Teaching labs are, as expected, less energy intensive than research labs with otherwise similar properties[21].

The above results are promising because they show that (nominally) higher efficiency buildings receive higher energy performance scores. However, no clear pattern is seen for most other building properties expected to have significant effects on energy consumption.

Figure 17 shows three examples: no significant correlation is seen between energy score and reported lab minimum air change rate[22], reported efficiency of design, or HVAC control system type.

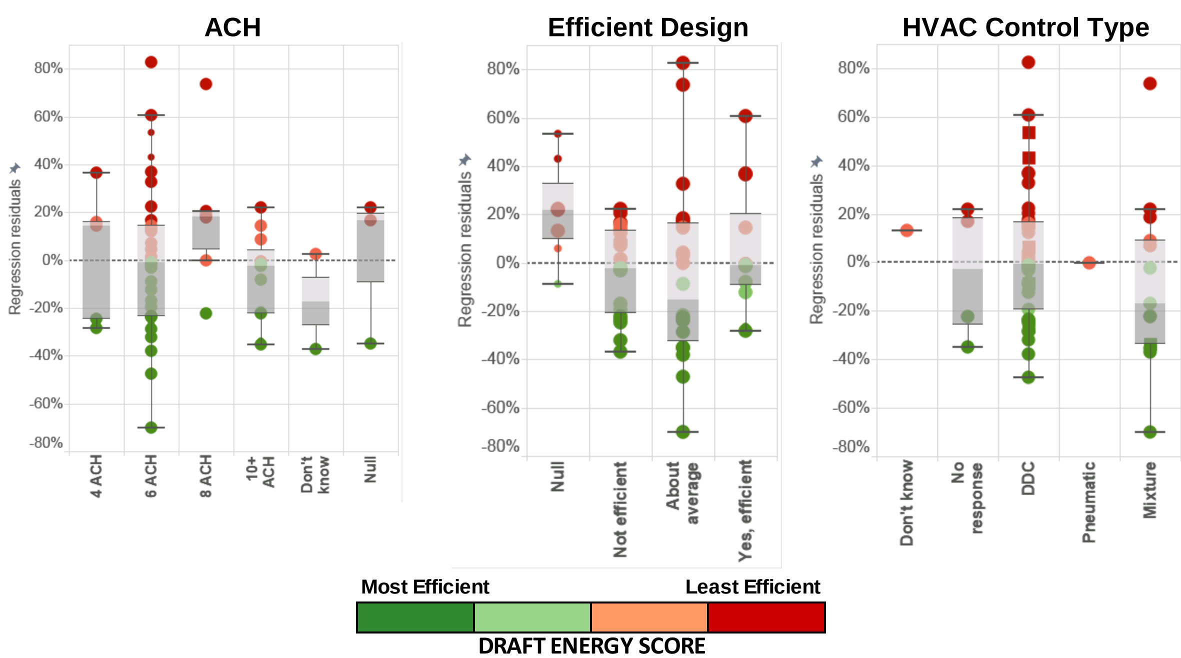

Figure 17: Distribution of Residuals by Reported Lab Minimum Air Change Rate (Left), Reported Efficiency of Design (Middle), and HVAC Control Type (Right). Data Point Colors Represent Energy Rankings.

The absence of expected patterns in the data does not mean that there is no potential for a reasonably equitable ranking system for lab building efficiency. While building energy consumption, total area, lab area, and decade of construction were generally provided for each building, a significant number of facility responses on other building system properties were blank, misinterpreted, or entered as “don’t know.” The unreliability of this part of the dataset

21 Lab purpose (teaching vs. research) is technically a functional requirement of the building; it was not included in the correlations because of the small number of teaching labs in the sample.
22 Note that air change rate data, while enormously important to energy consumption, are notoriously difficult to obtain in any consistent way.

makes the current assessment challenging. Further investigation, and potentially revisiting blank or incorrectly filled out data fields, is recommended.

The energy score analysis would also benefit from the inclusion of additional data points (perhaps from local biotech or pharmaceutical companies) and of additional regression variables such as a measure of research intensity (perhaps from space planning personnel). While benchmarking analysis of other process-driven facility types benefit from a normalization to production levels (widgets produced per year) instead of building area, it is difficult to see how this type of normalization could be applied to research lab facilities. Further, a significant portion of lab energy consumption results from ventilation requirements – these are typically based on space area (or volume) and are therefore well-suited to area-based normalization.

6. Conclusions and Next Steps

Whole building energy benchmarking is a high-level activity best used to prioritize attention within a portfolio of buildings or to catalyze discussion on the energy consumption patterns of a particular facility. Truly “fair” comparisons between buildings require detailed inventories of building functional requirements. For lab buildings (far more than for most other building types), functional requirements are numerous and highly varied; the desire to collect exhaustive data on these requirements must be balanced against the need to receive accurate data within a reasonable timeframe. This limitation does not negate the usefulness of lab benchmarking, but means that any resulting ranking of building energy efficiency must be used with caution. Critically, functional requirements not included in the ranking system may still have a significant impact on the energy consumption of any given lab building.

Lab building energy consumption is not mysterious: there are many well-understood reasons for the high energy consumption of lab facilities, e.g. required 24/7 ventilation, high-intensity research equipment, and high ventilation rates for occupant safety. For any given building, the total energy consumption can be understood in detail given sufficient time and resources. At some point, however, this activity can no longer be called “benchmarking” and would most likely be classified as energy auditing. The consequence of poor energy rankings deriving from energy disclosure ordinances tends to be mandated energy audits. It is not unreasonable to target buildings with anomalous energy consumption in this way, to establish whether there might be potential for energy savings at the facility. The initial benchmarking exercise is not well-suited to any system of public shaming or penalties, certainly not without an opportunity to provide additional explanatory information on anomalous energy consumption.

Public comparison and ranking is inevitable when energy usage data is released. The GRC study has demonstrated that the energy consumed by higher education lab buildings in the Boston area is similar to that seen in the nation as a whole. There appears to be potential for an equitable comparison of at least biology/biochemistry and chemistry facilities, but further investigation and development is required before any rankings can be made public.

A number of useful next steps are clear, including:

- Incorporating other labs from the Boston area to the dataset, e.g. biotech and pharmaceutical labs. Essentially the same survey questions could be used; it is expected that this could double the number of buildings in the sample.
- Incorporating a further year of utility data. Examining the differences between 2014 and 2015 data will help to identify data issues and will allow assessment of the degree to which energy rankings depend on the year of data chosen.
- Investigating other functional requirements, e.g. density of research activities. This may require communication with space planning personnel.
- Providing individual institutions with energy reports on their buildings
- Submitting the data to the Labs21 database as a resource for the industry as a whole. Note that online searchable data are anonymized.
- Revisiting the energy score outliers and investigating the reasons for their apparently anomalous energy consumption levels.
- Revisiting missing or misleading building data to increase the richness of the dataset.
- Extending data collection efforts to include annual facility water usage.