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### Title

Right-Sizing Laboratory Equipment Loads

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# LABORATORIES FOR THE 21<sup>ST</sup> CENTURY: BEST PRACTICE GUIDE

## RIGHT-SIZING LABORATORY EQUIPMENT LOADS

### Introduction

Laboratory equipment such as autoclaves, glass washers, refrigerators, and computers account for a significant portion of the energy use in laboratories. However, because of the general lack of measured equipment load data for laboratories, designers often use estimates based on “nameplate” rated data, or design assumptions from prior projects. Consequently, peak equipment loads are frequently overestimated. This results in oversized HVAC systems, increased initial construction costs, and increased energy use due to inefficiencies at low part-load operation. This best-practice guide first presents the problem of over-sizing in typical practice, and then describes how best-practice strategies obtain better estimates of equipment loads and right-size HVAC systems, saving initial construction costs as well as life-cycle energy costs.

This guide is one in a series created by the Laboratories for the 21<sup>st</sup> Century (“Labs21”) program, a joint program of the U.S. Environmental Protection Agency and U.S. Department of Energy. Geared towards architects, engineers, and facilities managers, these guides provide information about technologies and practices to use in designing, constructing, and operating safe, sustainable, high-performance laboratories.

### Equipment Load Estimation – Typical Practice

HVAC systems are sized based on a peak condition that takes into account climate-related loads and internal loads from occupants, lighting, and equipment. For some of these parameters, there are well-established criteria for peak conditions (e.g., design days for climate), while for others, the designer has to use context-specific information (e.g., load diversity) and engineering judgment to determine a peak load. This is especially the case with equipment loads, for which there is uncertainty about several factors:

- Quantity and type of equipment: While this is analyzed and documented by laboratory planners during the programming phase of design, the actual quantity and type of equipment installed will vary over the life cycle of the laboratory.
- Rated vs. actual power: For most equipment, the rated (“nameplate”) power is much higher than the actual power, even when the equipment is in full operating mode.
- Schedule of use: Even if the designer has good estimates of the first two parameters, the schedule of use is very difficult to derive deterministically, because it



is largely driven by user behavior, and the complete inventory of installed equipment is typically not used simultaneously.



The ASHRAE *HVAC Applications Handbook 1999* [ASHRAE 1999, p. 13.2] recommends that the designer "...should evaluate equipment nameplate ratings, applicable use and usage factors, and overall diversity."

However, due to the lack of data on these parameters, it is often difficult to analytically derive the equipment loads.<sup>1</sup> As a result, designers typically assume the worst case for each of these parameters, thereby grossly overestimating actual equipment loads [Wilkins 1998, Wilkins and Hosni 2000 cited in Brown 2002]. Furthermore, designers assume that the worst-case equipment load will be simultaneous with the worst-case climate loads. In short, conventional engineering methods chronically over-size HVAC systems. Brown [2002] cites several examples, including one in which, even after the size of the cooling plant was halved, the as-installed plant still had twice the capacity needed to meet the actual loads of the fully occupied building. An analysis of 26 laboratory projects by Martin [2004] showed that the over-sizing of cooling systems in these projects ranged from 40% to 300%, with an average of about 80%.

Data from the Labs21 benchmarking database provides further insight [Mathew et al. 2004]. The database contains data on energy use and demand for about 70 laboratory facilities. Figure 1 shows the total electrical demand for the facilities for which measured peak demand data were available. The facilities include various types of laboratories in several different climate zones. The data show that none of the facilities have *total* peak

electrical loads of more than 15 W / gsf. Note that this metric includes *all* electric end uses, i.e., HVAC, lighting, and equipment. Yet, it is common for designers to assume equipment loads *alone* at 10-12 W / sf or more. While this assumption may be appropriate for a few high-intensity lab spaces in a building, it would be unreasonable to assume such high loads building-wide.

### Case Study: Measured vs. Estimated Loads

The University of California, Davis (UC Davis) initiated a project to measure equipment loads at two of its laboratory buildings in order to use the measured data as a basis for sizing the HVAC systems in the design of new, comparable facilities. In each building, measurements were made for several laboratory spaces, representing a range of different uses within that building. Clamp-on meters were used to take continuous measurements of equipment electrical loads for each lab space. Each measurement period was typically about two weeks long. The measurements were taken when the labs were nominally fully occupied and used. Three quantities were measured, as follows:

- Apparent instantaneous power: The product of the voltage and the current at any given instant. This number is important because it informs the sizing of the electrical distribution system.
- Actual instantaneous power: This is the actual instantaneous power draw, which becomes a thermal load to the space.
- Average interval power: This is obtained by averaging the actual instantaneous power over each 15-minute

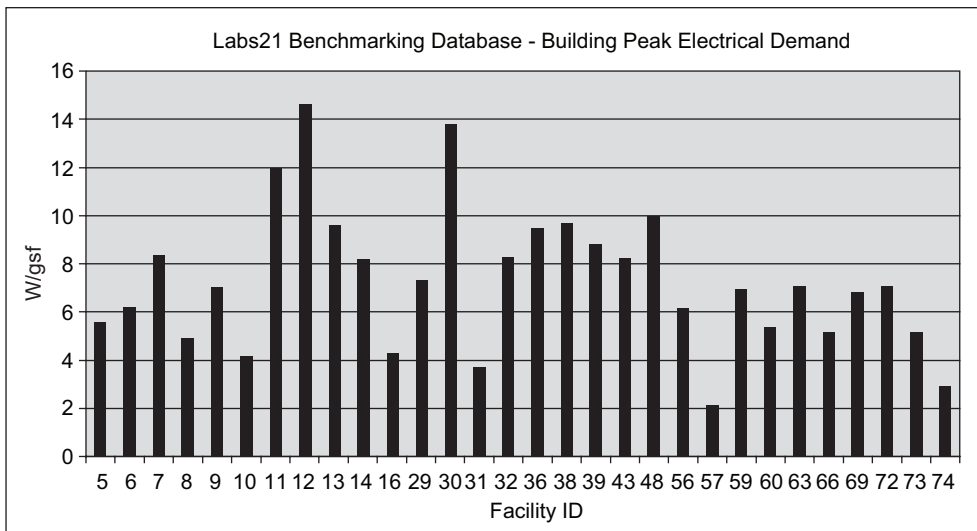


Figure 1. Total electrical demand (W/gsf) for various laboratory facilities recorded in the Labs21 energy benchmarking database.

<sup>1</sup>ASHRAE indicates that heat gains in laboratories range from 5 W / sf to 25 W / sf, but there are no additional data that would narrow this range for use in the design of a specific laboratory.



interval. This quantity is typically measured by utility interval meters to determine demand charges.

Figure 2 shows the 15-minute-interval measured data for two laboratory spaces, each of which was measured twice (about four weeks total for each space). The figure shows the peak apparent instantaneous power (in VA/sf), peak actual instantaneous power (in W/sf) and the average interval power for each 15-minute interval (also in W/sf). As expected, in each interval the peak apparent power is always equal to or higher than the peak actual power,<sup>2</sup> which in turn is always higher than the average interval power. In space A, the overall peak apparent power is about 8 VA/sf, and the overall peak actual power is about 7.5 W/sf. The maximum interval power is only about 3.75 W/sf, which is less than half the overall peak apparent power. In space B, the overall peak apparent power is about 40 VA/sf, and the overall peak actual power is about 29 W/sf, while the maximum interval power is about 6 W/sf, which is only 15% of the overall peak apparent power.

Generally, space temperatures are not sensitive to instantaneous peaks of a few seconds, and, therefore, it is unnecessary to size HVAC systems to peak instantaneous power. (The only exception to this would be in highly specialized labs with equipment, processes, or instrument calibration requirements that require space temperatures to be very tightly controlled.) In most situations, it is more appropriate to size HVAC systems to the maximum interval power. Yet, it is not uncommon for designers to assume equipment loads that even exceed the peak instantaneous

power. Figure 3 compares the measured loads to the assumed design loads for several different laboratory spaces in one of the buildings at UC Davis. This shows that the design assumptions were 2 to 5 times the peak instantaneous power, and were a whole order of magnitude above the maximum interval power. Evidence from laboratory designers and planners suggests this is not unusual and occurs widely in laboratory design practice.<sup>3</sup>

## Best Practice Strategies

### 1. Measure equipment loads in a comparable lab.

The Labs21 Environmental Performance Criteria [Labs21 2005] has a credit for right-sizing that recommends the following approach:

*“...For each comparable laboratory space, obtain one week (7 days) of continuous power metering at a distribution panel level of all laboratory equipment, including plug loads and hard-wired equipment....Metering data should be obtained while the spaces are fully occupied. Continuous metering data should be time averaged over 15 minute time periods. Design heat load criteria for each typical laboratory space in the facility should then be based on the maximum load indicated over the metering period....”*

It should be noted that this approach represents a minimum requirement, and longer or more detailed measurements may be required for specialized situations.

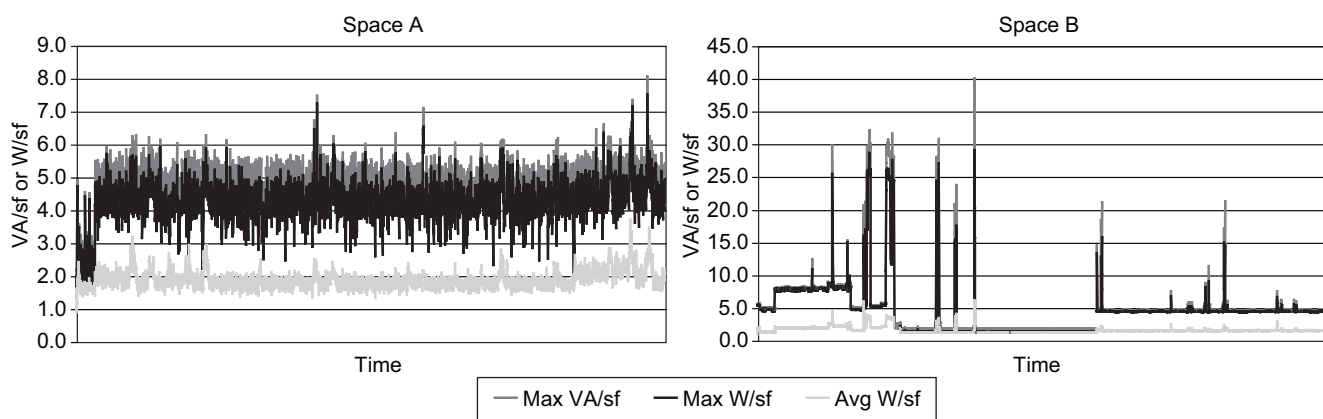


Figure 2. 15-minute-interval measurements of equipment loads for two laboratory spaces in the UC Davis building. Each graph shows peak apparent instantaneous power (Max VA/sf), peak actual instantaneous power (Max W/sf), and average power (Avg w/sf) in each interval.

<sup>2</sup> The ratio of actual power to apparent power is the power factor, which is always less than or equal to 1.

<sup>3</sup> It is important to note that the sizing approach for electrical systems is different from HVAC systems. The electrical designer is more constrained by the National Electrical Code, and other code and safety constraints. HVAC designers have much greater latitude in their approach to sizing. HVAC constraints are largely self-imposed, consisting primarily of the “code of common sense” and the risk of liability.

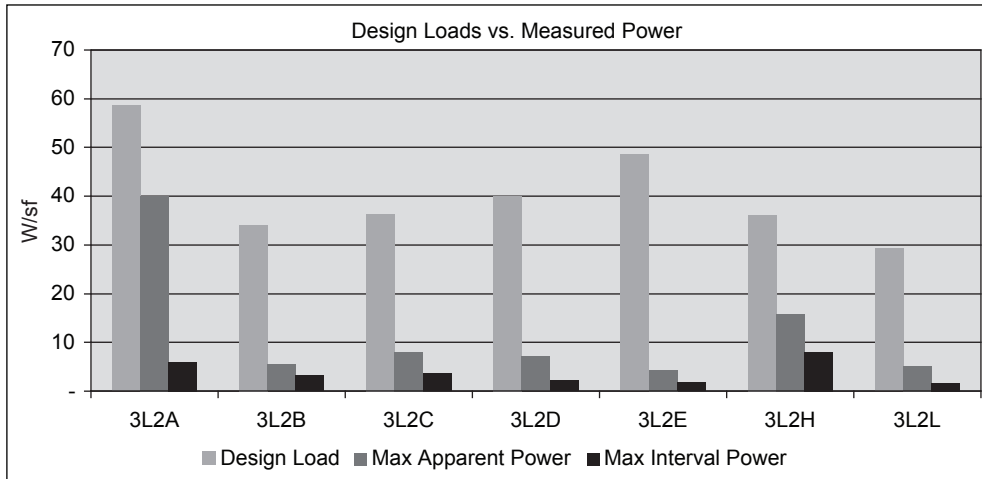


Figure 3. Comparison of equipment power used for design, measured peak apparent (instantaneous) power, and maximum interval power for various laboratory spaces at UC Davis.

Measurements can be made easily with commercially available data loggers. Some utilities have data loggers available on loan from their DSM programs. The usual configuration has the current transformers (CTs) and voltage connections inside the panel, and the actual logger outside the panel. This requires the wires to run out through a partially closed door. Most authorities allow this configuration for temporary connections, and typically no special provision needs to be made for it (the CTs and voltage connections coexist with what is already in the panels).

In the design for the new Molecular Foundry laboratory at Lawrence Berkeley National Laboratory (LBNL), measured loads were used to right-size HVAC and process cooling equipment, resulting in reductions in mechanical system sizing of over 30%, electrical transformer and distribution sizing of over 35%, and standby generator sizing of 20% (reductions are relative to the base case, which used estimated loads). The first-cost savings not only funded additional green design features, but also resulted in a net savings compared to the original construction budget (see the sidebar on page 5 for more information).

## 2. Use a probability-based approach to assess load diversity.

This approach uses a probability analysis to derive design loads based on the probability of simultaneous peak use of equipment. It is essentially a “bottom-up” approach to calculating diversity. While the depth and rigor of the analysis can vary, the approach essentially involves the following steps:

- For each type of heat source in a space, determine the number of sources and their peak outputs. This could be based on actual pieces of equipment, or the number and type of electrical and other outlets (as a proxy for equipment heat output). This information is often available from the programming documents.

- For each type of heat source in a space, determine the likelihood that it will be used. These data are typically obtained empirically through measurements or surveys.
- Use probability formulae or other statistical techniques to calculate the peak simultaneous load for the space, using the parameters described above for each heat source.

A major benefit of this bottom-up approach is that it provides a structured and logical way to calculate diversity factors for different levels of aggregation; i.e., as the number of pieces of equipment increases, a greater diversity can be assumed. For example, a building with 200 fume hoods can assume much more diversity than one with 20 fume hoods.

A more detailed description of this approach is provided by Martin [2004], who estimates the cost of probability analysis to be about \$0.50/sf. This is easily offset by the savings from right-sizing, which are conservatively estimated at about \$7.50/sf for HVAC and piped utilities in laboratories.

## 3. Allow for flexibility and growth, especially in the distribution systems.

HVAC systems should be right-sized and configured to allow flexibility and growth. In the “plant” this will require provision of access and space for new equipment. For example, the initial design may call for three chillers with the potential to add two more. In the distribution systems, at a minimum, shaft and ceiling space should allow for future expansion. Additionally, passive components such as ducts, pipe, and wiring should be sized for the maximum potential loads. Increasing the capacity of these systems as a retrofit is extremely costly and often inefficient. On the other hand, the incremental cost for extra carrying capacity in new construction is minimal, and provides significant flexibility in the future. Further, even if the load does not materi-



alize, the lower pressure drops and resistances result in improved energy efficiency. There are also first-cost savings in the active components (pumps, fans, and their motors; starters or variable-speed drives; and the electrical distribution system).

#### 4. Compare design loads with most-likely maximum (MLM) loads.

Traditional design loads are chronically overestimated because designers assume that the worst-case equipment load will be simultaneous with the worst-case climate loads, while allowing large margins of safety and little consideration of diversity. One way to assess the potential for right-sizing is to compare the design loads to the “most likely maximum” (MLM) loads. This approach was developed and used in right-sizing the central plant at the new University of California, Merced campus [Brown 2002].

To avoid over-sizing the central plant for the new campus, the owner used measured benchmark data from other campuses to right-size the plant. Instead of just using design values that assume a worst-case estimate, a “most likely maximum” (MLM) load was also determined, based on the actual measured maximum loads in comparable buildings. Design for efficient operation at MLM load can be mandated, and the difference between the MLM and the design loads can be value-engineered to reach a reasonable margin of safety for each subsystem.

#### 5. Configure equipment for high part-load efficiency.

Plant equipment, including fans, pumps, chillers, and boilers, should be configured for high efficiency even at very low part-loads. Even if the equipment has been right-sized for the peak load, the load fluctuates widely, and the equipment operates at low part-loads many if not most hours of the year. Therefore, it is advisable to design the system for high efficiency at low loads. One solution is a modular plant design, where only the number of units needed are run. The design can accommodate increases in the load by adding modules. For example, at LBNL, two large, aging boilers with high mass and high standby loss were replaced by eleven modular low-mass boilers (Figure 4). Thus far, no more than seven of these have been required to meet peak loads. Plant designs with multiple modular primary components and optimized lead-lag logic programs will increase run-time hours at or near the peak efficiency of each primary component as compared with plant designs with one or two primary components for each major system, thereby increasing the average plant efficiency.

### Right-sizing the Molecular Foundry Laboratory at Berkeley Lab

The Molecular Foundry laboratory (MFL) at Lawrence Berkeley National Laboratory (LBNL) is a Labs21 Partner project that rated its green design using the Labs21 Environmental

Performance Criteria (EPC) in addition to the USGBC LEED rating system. EPC credit EA 9.1 calls for measuring equipment loads in



comparable spaces to inform the sizing decisions. LBNL and the design team measured actual loads in three other laboratory buildings at the LBNL campus, and the electrical and mechanical systems were downsized by roughly one-third, resulting in a savings of about \$2.5 million. These savings covered the LEED compliance “hard” (construction) costs of just over \$400,000, with money to spare. The \$2.1 million in net savings represented over 4% of the total construction costs of the project.



Figure 4. LBNL replaced two boilers with 11 modular boilers to maximize part-load efficiency.





Another common strategy is to use variable-speed drives on equipment that operates at part-loads. Figure 5 shows the energy use impact of variable-speed drives on chiller operation for various part-loads. Fan and pump applications typically show even greater savings.

## 6. Negotiate risk management between owner and designers.

The most common argument against right-sizing is the risk of under-sizing and the question of who carries that risk. As many design engineers have observed, the legal and contractual basis for design services rarely rewards right-sizing, and almost certainly will penalize under-sizing. Right-sizing requires that owners and designers come to an agreement on the basis for right-sizing and the associated need for risk management. This requires a shared understanding of and agreement on parameters such as peak occupancy characteristics, laboratory equipment loads, and load diversity assumptions. Designers should provide owners with information on the first-cost and operating-cost penalties for different degrees of over-sizing so that owners can make an informed decision on the tradeoffs.

## 7. Include energy efficiency in the procurement process.

By incorporating energy efficiency criteria into the equipment procurement process, owners can reduce equipment loads and obtain better estimates of actual equipment energy use. Furthermore, they—and especially high-volume purchasers—can create a market “pull” to develop more energy-efficient laboratory equipment. For example:

- Where available, specify EnergyStar™ equipment. Many of the refrigerators and computers used in laboratories are standard commercial products for which EnergyStar™ choices are available. EnergyStar™ also

provides energy use information that can be used to estimate total loads.

- For equipment types that do not have a rating system such as EnergyStar™, request energy use information from manufacturers. At a minimum, this should include energy use for three operating modes: peak mode, typical (nominal) mode, and dormant (“sleep”) mode. This information can be used to compare the energy use of functionally equivalent options, as well as to estimate total loads.

Stanford University conducted a survey of their laboratory refrigerators and found a significant opportunity to reduce energy use and peak demand. Stanford then decided to include energy efficiency as a criterion in procuring laboratory refrigerators, and required suppliers to provide energy use data in their bids.

## Benefits of Right-Sizing

A study by Enermodal and the National Renewable Energy Laboratory (NREL) [2003] demonstrates the influence of the design assumption for plug loads on the sizing of mechanical equipment. The analysis was conducted on a prototypical 100,000-sf laboratory building, in different climate zones. The base-case system is constant volume, with a minimum ventilation rate of 2 cfm/sf. The base-case equipment load is 12 W/sf, which corresponds to an “over-size” load, and parametric cases were modeled with “right-sized” loads of 8 W/sf and 4 W/sf. Figure 6 illustrates the reduction in total chiller tonnage from right-sizing. For example, in Atlanta the assumption of 8 W/sf results in a reduction of 100 tons of cooling, while the assumption of 4 W/sf results in a reduction of about 200 tons. The analysis by Martin [2004] computed the cost of over-sizing HVAC and piped utilities in laboratory projects to be at least \$7.50/sf, and more likely to be two or three times that, depending on the extent of over-sizing.

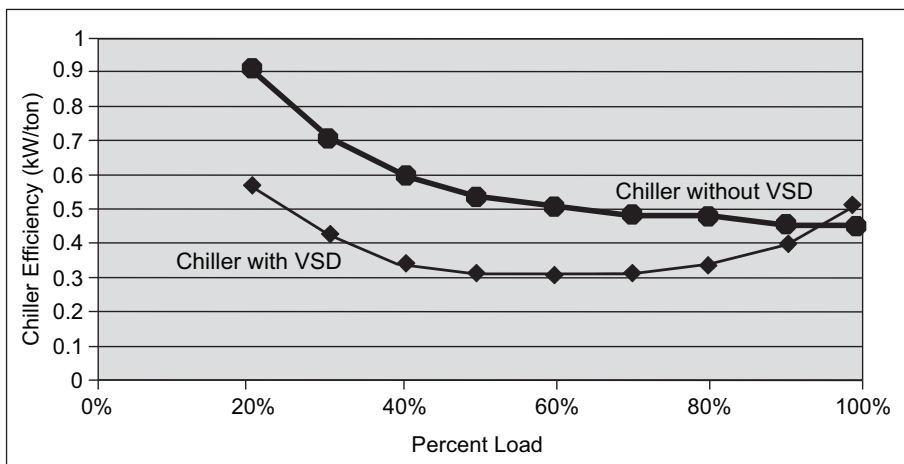


Figure 5. Variable-speed drives are a common strategy for maximizing efficiency at part-loads. Data provided by York International Corporation for chillers running at 42°F chilled water supply and 65°F condenser water supply.

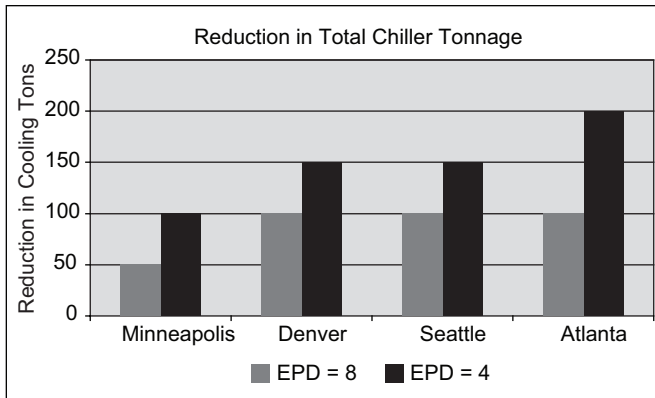


Figure 6. Reduction in chiller tonnage resulting from right-sizing equipment power density (EPD) down from 12 W/sf, to 8 W/sf and 4 W/sf, for different climatic contexts. Based on parametric simulation study of a prototypical 100,000-sf laboratory building [Enermodal and NREL 2003].

Another benefit of right-sizing is the reduction in energy use that results when equipment is operated at higher part-load ratios. Figure 7 shows the change in energy use resulting from over-sizing HVAC equipment. Energy simulations were conducted for three cases:

- Base case: HVAC systems were sized for an equipment load of 6 W/sf.
- Oversize case 1: HVAC components were about twice the size of the base case.
- Oversize case 2: HVAC components were about three times the size of the base case.

For boilers, chillers, and pumps, energy use goes up with over-sizing. In the case of fans, energy use goes down, because with variable speed drives, fan power can follow the cube law, i.e., fan power decreases as much as a cube function of airflow. (Therefore, a fan running at 75% of full flow consumes less than 50% of the energy use at full flow.) The total site energy use (all end uses) increases by about 4% for over-size case 1 and by about 10% for

over-size case 2 in the Washington, DC, climate.

Some designers suggest that equipment load is not relevant to right-sizing, because HVAC equipment sizes are driven by ventilation requirements, not equipment loads. While this may be true in some instances (e.g., laboratories with low equipment loads and high minimum ventilation rates), it cannot be generalized. It should also be noted that ventilation requirements themselves are often set at an unnecessarily high level. Some organizations have recently revisited their minimum ventilation requirements and revised them downward. The chiller tonnage analysis above, which assumed a 2 cfm/sf minimum ventilation requirement, clearly shows that equipment loads affect chiller tonnage in a wide range of climatic conditions. It is recommended that designers at least do a sensitivity analysis during design, to assess the impact of equipment loads on HVAC sizes.

### Conclusion

Equipment load measurements from various laboratories showed that peak equipment loads are significantly overestimated. Evidence from laboratory designers and planners suggests this is not unusual and occurs widely in laboratory design practice.

When designing a laboratory HVAC system, the use of measured equipment load data from a comparable laboratory can effectively support right-sizing HVAC systems, saving initial construction costs as well as life-cycle energy costs. The minor cost of measuring a comparable laboratory is far outweighed by the potential benefits of using the data to reduce HVAC system sizes and energy use. Additionally, probability-based analysis provides a structured and logical way to derive diversity factors for equipment loads. The most common argument against right-sizing is the risk of under-sizing and determining who carries that risk. Right-sizing requires that owners and designers come to agreement on the basis for right-sizing and the associated risk management.

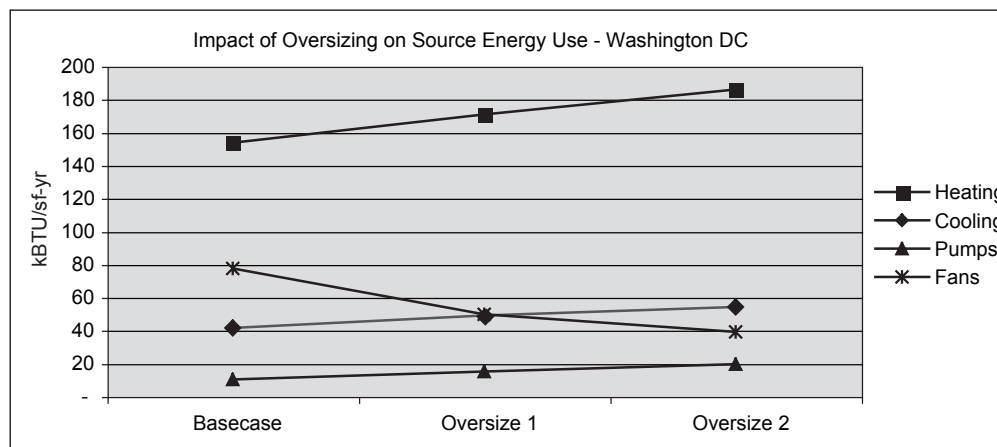


Figure 7. Change in energy use resulting from over-sizing. Base case: 6 W/sf design load. Over-size 1: HVAC systems sized 2x base case; Over-size 2: HVAC systems sized 3x base case.





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