Best Practices Guide

# An Introduction to Low-Energy Laboratory Design

AUGUST 2021

## Introduction

In the early 1970s, energy demand in the U.S. was outpacing the country's oil production, and an oil embargo in 1973 led to an energy crisis. As it emerged from this predicament, the U.S. recognized the importance of increased energy efficiency in lowering energy demand. To cut operating costs, many office buildings greatly reduced the amount of outside air provided through their HVAC systems. But the lack of adequate ventilation led to increases in mold and other allergens, and some occupants became ill with a malady termed "Sick Building Syndrome." To address these issues, the National Bureau of Standards (NBS) began creating standards for both minimum ventilation and energy efficiency.

A common measure of a building's annual energy efficiency is Energy Use Intensity (EUI), measured in 1,000 British thermal units (Btus) per square foot per year (kBtu/sq ft/yr). Numerous factors can impact EUI, including building use, configuration, orientation, climate, mechanical/electrical/plumbing (MEP) systems, and more. A facility in Denver will not have the same EUI as an identical one in Phoenix or Miami.

Building program and climate are strong drivers of EUI. Offices generally contain some equipment, but space conditioning is usually determined by the need for occupant comfort. Office air may be recirculated provided a minimum amount of ventilation is maintained. Laboratories have higher energy consumption due to their need for tighter environmental controls and increased ventilation, as well as the inability to recirculate laboratory air to other zones due to safety concerns. A single fume hood may consume as much energy annually as three typical homes.

In 1995, the U.S. Energy Information Administration's Commercial Buildings Energy Consumption Survey (CBECS) indicated that office buildings had an EUI approaching 100 while the average laboratory building had an EUI closer to 240 (U.S. Energy Information Administration, 1995). At the time, the country's total energy consumption was approaching 90 quadrillion Btus.

Progress has been made in facility energy efficiency since then, with growing concerns about global climate change lending urgency to the effort. In 2018, the average office listed in the ENERGY STAR Portfolio Manager had an EUI of 53, and the average laboratory EUI was 115 (U.S. Environmental Protection Agency, 2018). Comparing these stats with those from CBECS 1995 shows that continued improvement and implementation of energy standards — from structure to appliances, electrical transformers to mechanical equipment, envelope to lighting — have cut building energy usage in half in less than 25 years.

Despite the improvement in buildings' average EIU, the nation's demand for power overall has not declined. In fact, from 1995 to 2018, energy consumption grew from 90 quadrillion to more than 100 quadrillion Btus (Figure 1, page 2). If this amount of energy were used all at once to heat the water of the five Great Lakes, the average water temperature in these lakes would rise by more than 50°F.

A closer look at the nation's 2019 energy use reveals that energy consumption is divided among transportation, industrial, commercial, and residential sectors (Figure 2, page 2). More than half of the country's energy usage occurs in buildings, including a relatively small number of

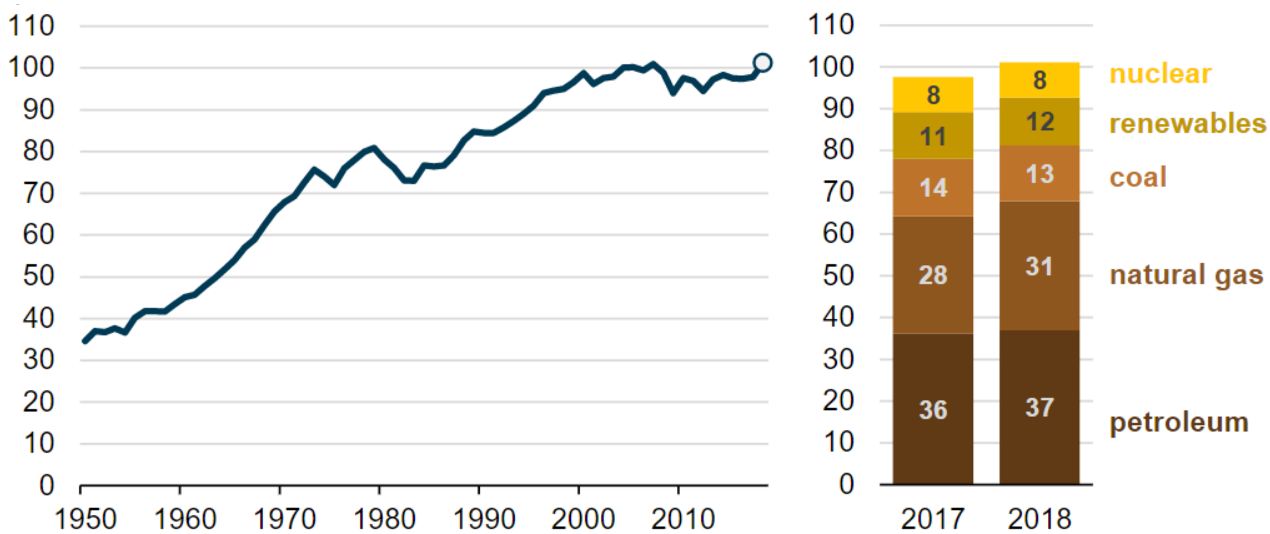


*Figure 1. U.S. total energy consumption (1950-2018), in quadrillion Btus. Source: U.S. Energy Information Administration, 2019.*

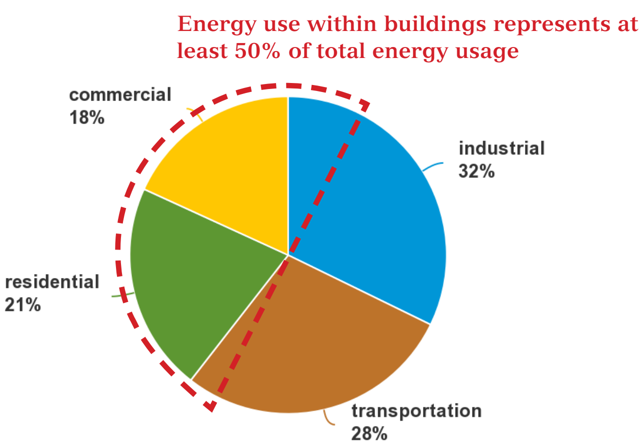


*Figure 2. Share of total U.S. energy consumption by end-use sectors (2019), totaling 100.2 quadrillion Btus. Sum of individual percentages does not equal 100 because of independent rounding. Source: U.S. Energy Information Administration, 2020.*

buildings within the industrial and transportation sectors. Though residential facilities are generally less energy-intensive than commercial, there are many of them, and they generally have less efficient building systems. Thus, they account for higher overall energy use. However, the greatest push in energy efficiency improvements has been, and continues to be, within the commercial sector.

Overall, the architecture/engineering/construction (AEC) field has strongly embraced the goal of reducing energy consumption and related greenhouse gas emissions by buildings, including labs. Architecture 2030 was founded as a nonprofit in 2002, and its 2030 Challenge was adopted in 2006 by the American Institute of Architects (AIA) as the basis of its 2030 Commitment (Figure 3, page 3).

The initiative was conceived in response to the increased demand for energy outpacing the savings from improvements in energy standards. The goal is to improve energy efficiency in buildings and establish a pathway to a 100% reduction in carbon dioxide emissions from fossil fuels by the year 2030 (Architecture 2030, 2021). Trending and benchmarking data for building EUIs are gathered and shared, and milestone targets help ensure that the implementation remains on track.

As of 2020, building performance had significantly improved compared with 2006 but was not on track to achieve the goal of carbon neutrality by 2030.

Taking the next step in energy efficiency requires a holistic view of energy use. Laboratories are among the building types that consume the

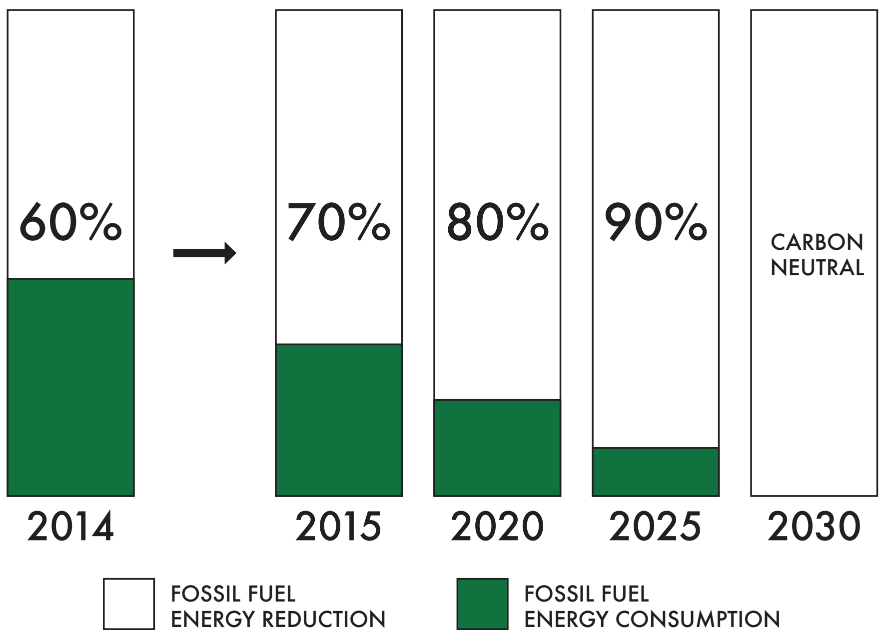


*Figure 3. The 2030 Challenge performance milestones. "Carbon neutral" is defined as using no fossil fuel greenhouse gas-emitting energy to operate. Source: ©2010 2030 Inc./ Architecture 2030.*

greatest amount of energy, and reducing lab energy efficiency can have a significant impact on building energy use overall. The U.S. government's recognition of this fact has spawned efforts such as Laboratories for the 21st Century (which later evolved into the nonprofit International Institute for Sustainable Laboratories, or I$^2$SL) and, more recently, the Department of Energy's Better Buildings Smart Labs Accelerator.

This publication takes a "big picture" view of the special difficulties and key opportunities of advancing energy efficiency in labs, including lab-specific strategies as well as general building programming, architecture, HVAC, and power considerations. For further details on many of the relevant topics, refer to the Resources section of the I$^2$SL website (i2sl.org/resources).

## The Laboratory Energy Challenge

The key differentiators between offices and laboratories are labs' greater equipment loads, higher ventilation requirements (for user safety), inability to recirculate air outside the space of origin (for the safety of others), and tighter environmental criteria. Though offices and labs share a core need to keep users safe and comfortable, the demand for increased ventilation quickly dominates energy use for most labs.

Recognizing this, energy codes require minimum 50% efficient (based on total energy of air) outside air energy recovery systems, depending on outdoor climate, system supply airflow, and the ability to reduce ventilation by more than 50%. Several approaches for recovering energy in laboratories are available, but their application is greatly influenced by the climate and building program (Van Geet et al., 2012). Note that the use of traditional energy wheels is prohibited in laboratories with chemical use due to the potential transfer of chemicals into the supply air.

Laboratory environmental health and safety (EHS) officers establish minimum occupied and unoccupied ventilation rates for laboratories, typically expressed in air changes per hour

(ACH). Many laboratories can safely operate at lower ventilation rates when unoccupied. While high-efficiency fume hoods are designed to operate safely at lower face velocities, EHS officers may require higher velocities when hoods are in use.

The laboratory program and layout also play a significant role in energy use. Locating larger fume hoods in small spaces increases ventilation demand regardless of fume hood efficiency, while locating fume hoods in alcoves adjacent to open laboratories takes advantage of the minimum ventilation of the open laboratory to lower the impact of the fume hood ventilation.

Optimal performance can also extend beyond building design. Situating complementary building programs close to each other may allow for significant energy improvements. For instance, large data centers and labs with high process cooling loads require continuous cooling. If these types of facilities are matched with a laboratory in a heating climate, active heat recovery systems may provide primary or supplemental heating to the lab while simultaneously cooling the complementary programs.

The energy efficiency challenges faced by labs are, in short, considerable. Recognizing this, the University of California Irvine (UCI) established its Smart Labs program in 2008 (Smart Labs Toolkit, 2021). With this initiative, the university has been able to cut its overall energy consumption in half over a 10-year period while continuing to grow and add laboratory programs (Figure 4). UCI identified many over-ventilated spaces — with increased fan energy and increased heating energy — where the minimum ventilation rate exceeded the cooling demand. Other high energy users included excess fan power for exhaust stacks (discharge velocity too high) and building systems that were not operating correctly.

Based on the results of the UCI Smart Labs

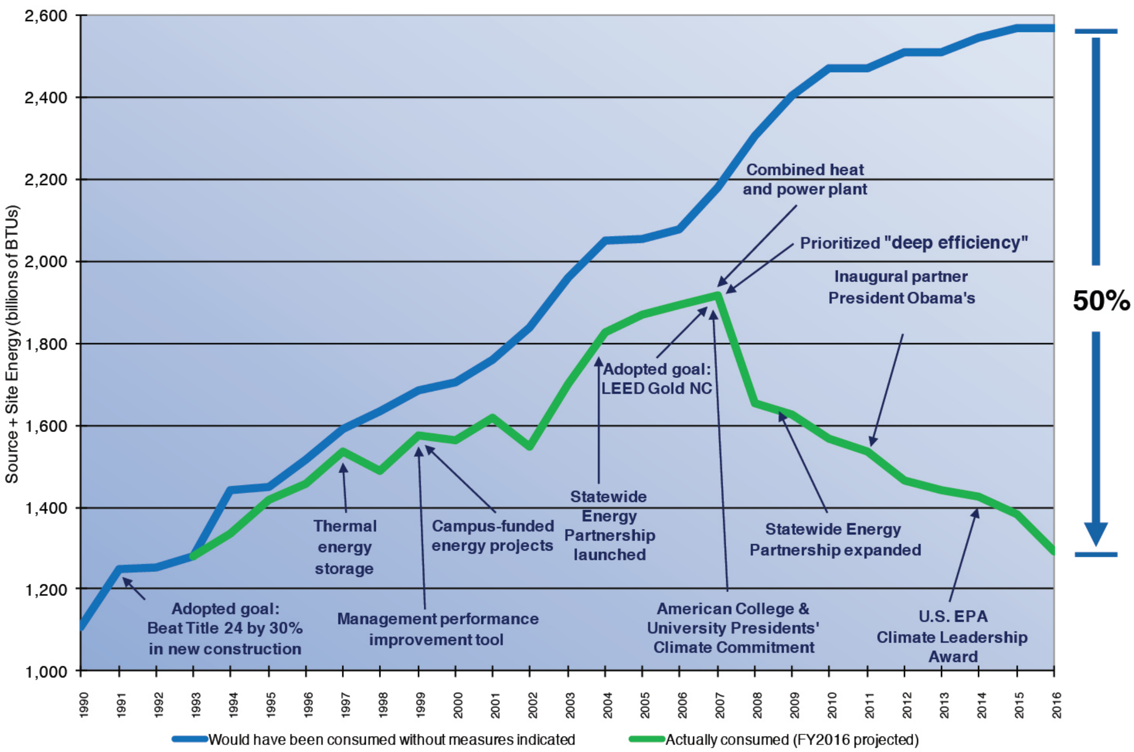


*Figure 4. UC Irvine Smart Labs Program projected vs. actual energy consumption (1990-2016). Source: Smart Labs Toolkit, 2021.*

program and the Better Buildings Smart Labs Accelerator (U.S. Dept. of Energy, 2021), I$^2$SL has created the Smart Labs Toolkit (https://smartlabs.i2sl.org/) to help laboratory managers and stakeholders improve the performance of their laboratory spaces. The toolkit takes a systematic approach to optimizing laboratory energy use while maintaining a safe environment for both the researchers and other staff who occupy these facilities.

## Energy-Efficient Lab Design: A Team Process

Optimal energy efficiency in laboratories requires multiple stakeholders to collaborate in the design of facilities that meet program needs, conserve energy, and optimize ventilation while avoiding overly complex control structures. For instance, architects and lab planners, together with researchers, work to right-size laboratory modules while limiting overall laboratory area and ventilation. Architects consider the envelope and fenestration to maximize available daylighting while limiting envelope losses and the need for supplemental space conditioning.

Putting mechanical systems in adjacent relationships to the laboratories they serve can reduce infrastructure (first cost) and lower distribution energy. Taller exhaust stacks or increased separation between laboratory exhaust and outside air intakes have the potential to lower stack velocities and save fan energy (Cochran & Carter, 2021). These types of decisions must come early in the design process, and must involve the mechanical design engineers, to allow optimal energy efficiency. (The box on page 6 points out some of the shortcomings of the Traditional Design Process and the benefits of an Integrated Design Process.)

Mechanical energy performance varies based on the climate, the program mix, the building size (scale of systems), the resources available, and the energy goals of the project. The mechanical systems matrix shown in Figure 5 provides a way to consider mechanical systems design in the context of building size (in increments of 1,000 square feet or KSF) and desired building performance, from code-minimum baseline to enhanced performance.

| | BASELINE | REFINED | ENHANCED |
|---|---|---|---|
| < 50 KSF | System Config: Local<br>Airflow Control: CV/VAV<br>Heat Rejection: Air<br>Heating Source: Electric<br>DOAS Recovery: 50% Enthalpy (Lab) | System Config: Local<br>Airflow Control: CV/VAV<br>Heat Rejection: Air/Evaporation<br>Heating Source: Electric/Gas<br>DOAS Recovery: 50% Enthalpy (Lab) | System Config: Central<br>Airflow Control: VAV<br>Heat Rejection: Air/Ground<br>Heating Source: Electric/Gas<br>DOAS Recovery: 50% Enthalpy (All) |
| 50–150 KSF | System Config: Packaged<br>Airflow Control: VAV<br>Heat Rejection: Air<br>Heating Source: Electric/Gas<br>DOAS Recovery: 50% Enthalpy (Lab) | System Config: Central<br>Airflow Control: VAV<br>Heat Rejection: Evaporation/Ground<br>Heating Source: Electric/Gas<br>DOAS Recovery: 50% Enthalpy (Lab) | System Config: Central<br>Airflow Control: 50% Reduced VAV<br>Heat Rejection: Evaporation/Ground<br>Heating Source: Electric/Gas<br>DOAS Recovery: 50% Enthalpy (All) |
| > 150 KSF | System Config: Central<br>Airflow Control: VAV<br>Heat Rejection: Evaporation<br>Heating Source: Electric/Gas<br>DOAS Recovery: 50% Enthalpy (Lab) | System Config: Central<br>Airflow Control: 50% Reduced VAV<br>Heat Rejection: Evaporation/Ground<br>Heating Source: Electric/Gas<br>DOAS Recovery: 50% Enthalpy (Lab) | System Config: Central<br>Airflow Control: 70% Reduced VAV<br>Heat Rejection: Evaporation/Ground<br>Heating Source: Electric/Gas<br>DOAS Recovery: 70% Enthalpy (All) |

*Figure 5: Sample mechanical systems design considerations matrix. Source: SmithGroup.*

The larger the building (and its energy use), the more efficient the baseline mechanical systems need to be to comply with the requirements of the energy code. Using natural gas for heating lowers heating costs but may conflict with fossil fuel reduction goals. As design moves from baseline to more enhanced and energy-efficient systems, mechanical systems become more passive, and fan energy is reduced.

Dedicated outside air systems (DOAS) with minimum 50% efficient exhaust energy recovery are required for baseline laboratory programs and other facility uses requiring high ventilation. To improve building energy performance, these approaches can be expanded to other programs, and other technologies can be considered to increase recovery efficiencies to 70% or more. Life cycle cost analysis (LCCA) can be used to calculate future energy savings that can offset increased first costs.

## Traditional and Integrated Design

The facility design process can have a significant impact on laboratory energy efficiency, as well as overall functionality and construction/operating costs.

Building design begins at Programming. The client articulates the needs and features of the building. Architects and planners, in understanding these requirements, determine the relative size of the program elements, the relationship of these elements to each other, and how the prospective program interfaces with the site elements. The MEP engineering team develops system narratives based on the program, code requirements, energy goals, and more. Civil engineers begin to understand site utilities, drainage, and roads, while structural engineers consider materials, column spacing, and other aspects of the building's ability to handle loads and forces.

In a **Traditional Design Process**, client interactions are, for the most part, limited to the architect and planner, who take what they learn and share that with the collective team.

Moving into Schematic Design, the building begins to take shape. Architects continue to meet with the client, fine tune program adjacencies with consideration for code-related requirements, and begin to weave in input from other team members. Engineering similarly refines system concepts and begins to share with the client for feedback. That feedback may inform alternate or modified solutions to meet the objectives of the client and the program.

As the Traditional Design Process continues into Design Development, coordination between disciplines ramps up. As engineering refines systems and requirements based on client feedback, any incorrect assumptions must be revisited and coordinated with the architectural team. If this process begins to impact program elements, accommodations must be made, or compromises sought, to allow systems to operate correctly. By the time the Contract Documentation phase begins, the plans and their requirements have ideally been well established, with each discipline finalizing documents for construction contracting and coordination.

The challenge with the Traditional Design Process is that for the first two phases, the architectural and engineering disciplines tend to operate in their own lanes with limited touch points and interactions. As they prepare to caravan into Design Development, the disciplines may find that they were not going in the same direction, forcing the team to regroup. Prior efforts may need to be revisited to get the team moving in sync, with some program features, previously achievable, abandoned due to schedule or cost limitations. Now aligned, the team pushes forward to the destination.

*continued on page 7*

## Traditional and Integrated Design, Cont.

By contrast, an **Integrated Design Process** brings engineering alongside early, allowing the design engineers to listen in on conversations between the architect and the owner to inform their narratives. Concerns or impacts to engineering systems can be raised and the client engaged to help inform the direction for the engineering systems. Program elements, previously driven primarily by the client with assumptions for engineering, now include engineering-specific elements. These additional elements are then woven into the concepts to be defined in the Schematic Design phase. Program features can now be accommodated earlier, with less potential for redesign.

The Integrated Design Process is a more interdisciplinary approach, involving all the key stakeholders much earlier than with Traditional Design. This method allows energy efficient strategies to be considered during Programming, Planning, and Schematic Design so that accommodations can be made with minimum impact to the project cost (Figure 6). While not all program changes can be foreseen, this approach provides the best opportunity to reduce first cost and allow implementation of energy improvement strategies. Any premiums for enhanced energy efficiency can be evaluated through life cycle cost analysis (LCCA) and/or carbon-reduction assessment.

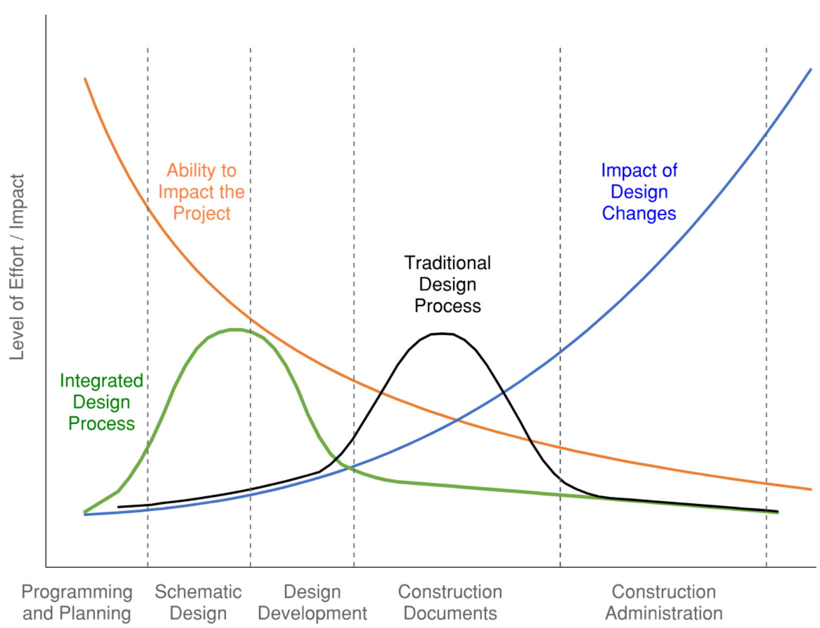


*Figure 6: Cost benefits of the Integrated Design Process vs. the Traditional Design Process. Source: SmithGroup.*

## Fundamentals for Low-Energy Lab Design

Though each laboratory facility is unique, a number of fundamental energy reduction strategies for labs are broadly applicable. These include:

- Conducting life cycle cost analysis (LCCA) with energy modeling
- Reviewing codes and standards
- Benchmarking against other lab buildings
- Avoiding overly narrow operating ranges
- Maximizing efficiency opportunities in lab and office programs
- Identifying the need for mini-environments
- Planning fume hood quantity, size, and location

## LCCA and Energy Modeling

Life cycle cost analysis and energy modeling should guide energy investment decisions. Energy modeling is a means to rank energy improvements based on their relative energy performance compared with a minimally code-compliant baseline building. Note that not all energy improvements are related to building systems. Shading can lower cooling costs, while improvements in glazing efficiency and envelope performance save on both cooling and heating.

Some improvements have the potential to save a significant amount of energy, but first costs may hinder their implementation. While an optimized approach balances both energy and cost, significant operational savings and/or carbon reductions may justify an additional budget allowance from funds set aside for energy improvement projects.

Cost consideration of alternatives should recognize savings within and among disciplines. For example, a laboratory with an active chilled beam system and active sensing of contaminants will have a higher first cost for these components, but a substantially lower cost for supply air units and lab exhaust systems and associated ductwork. Other first-cost savings in this example may include a smaller mechanical penthouse, potentially lower floor-to-floor heights (reduced materials cost), and reductions in electrical power and generator loads. All these potential savings need to be vetted and, where achievable, incorporated in the LCCA to highlight the true savings and payback of the energy investment decisions.

## Reviewing Codes and Standards

Building codes include specific requirements based on program elements and engineering systems and their configuration, as enforced by the authority having jurisdiction (AHJ). Typical AHJs include city, county, or governmental agencies responsible for enforcement. Standards, on the other hand, are seen more as guidelines unless those standards have been incorporated into the codes. For example, the ASHRAE Standard 62.1 for minimum ventilation shares many similarities with the International Mechanical Code (IMC) requirements for ventilation. Most AHJs will allow either the IMC or ASHRAE 62.1 to be used, provided all the requirements of the respective reference are followed completely.

Minimum ventilation rates vary significantly based on occupancy classification. A laboratory may contain hazardous materials, requiring increased levels of ventilation and prohibiting recirculation of air beyond the space of origin. In most facilities, this translates to single-pass air, involving lab supply paired with the associated lab exhaust. A laser laboratory in a physics program, however, may have a higher cooling load driven by temperature sensitivity, but without the presence of hazardous materials. Classifying this space as “hazardous” would force increased ventilation (and energy use) for a condition that may not require it.

Advanced sensor and controls systems can actively monitor lab air for chemicals and/or particulates, enabling significant reductions in ventilation and associated energy consumption whenever the chemicals are not present. Such systems, however, are tuned to a specific type of research and chemical use, and may need to be updated as lab programs change.

While standards may allow for increased duct or piping velocities based on material type and operating pressure to reduce infrastructure costs (first costs), these decisions will trigger increased operating costs due to the larger fans and pumps required. A balanced approach optimizes energy performance and first cost, while allowing future expandability.

Careful review of codes and standards, and conversations with the relevant AHJ, will always yield benefits and can pave the way for intelligent consideration and implementation of energy efficiency strategies.

## Benchmarking to Inform Goals

Beyond the minimally compliant building code analysis, the use of benchmarking data for peer facilities in the same climate region (or a similar region) will help inform energy efficiency goals. The I²SL's Laboratory Benchmarking Tool includes a database of an ever-growing number of facilities (I²SL, n.d.).

Within the Laboratory Benchmarking Tool, laboratories can be sorted by several factors beyond climate region, including laboratory function, size, percentage of laboratory space, density of fume hoods, and more (Figure 7). Building systems may also be compared to inform design solutions. By knowing how peer facilities in a given climate are performing, energy efficiency criteria and goals can be soundly established.

For more information about the tool, see Mathew et al., 2021a.

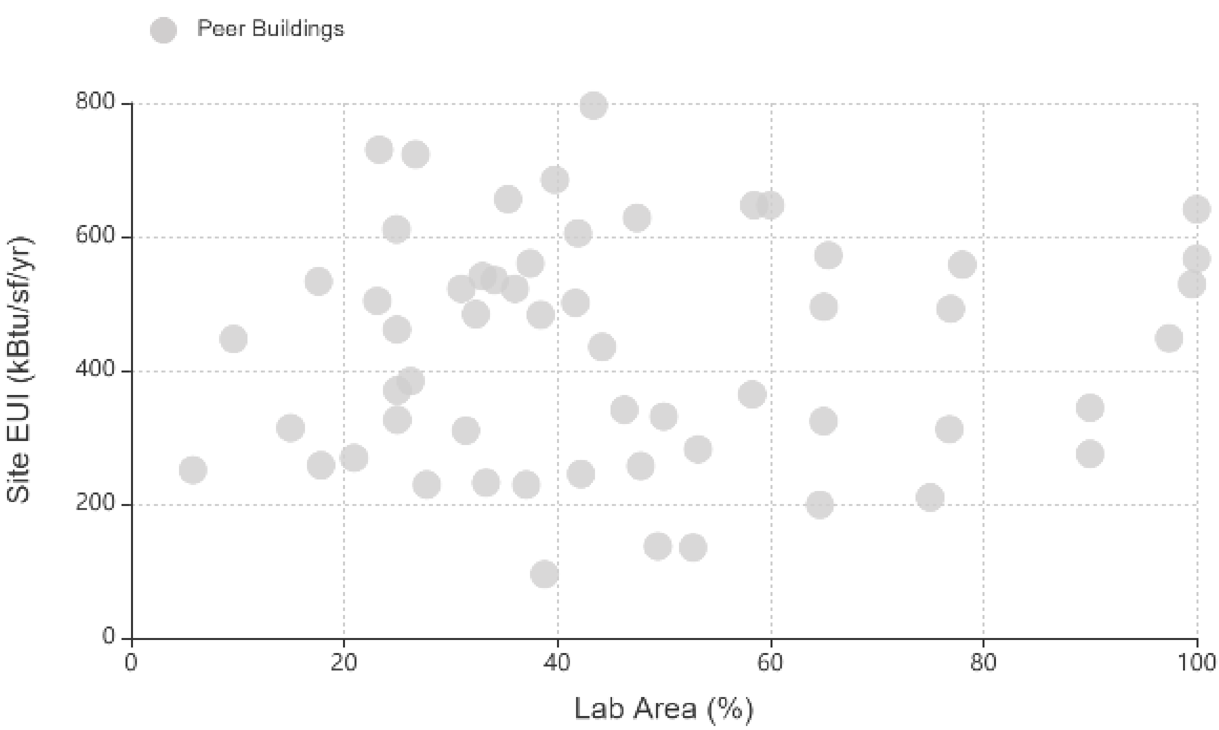


*Figure 7. Sample scatter plot from the I²SL Laboratory Benchmarking Tool of peer chemistry and biology program facilities (existing and new) in Climate Zone 4A (Mixed – Humid).*

## Avoiding Overly Narrow Operating Ranges

Some lab equipment and processes require tight temperature and humidity control, but most do not. Selecting operating criteria for an entire building based on a limited number of spaces will negatively impact operating and maintenance costs. Any energy used to increase laboratory humidity (or to excessively dehumidify) will be lost with the laboratory exhaust. Control systems that were otherwise straightforward may also become more complex to maintain these tight operating ranges.

Allowing for wider ranges in environmental criteria (temperature and humidity) allows mechanical systems to become more efficient and take advantage of more temperate outside air conditions (more free cooling).

Instrumentation or imaging labs are examples of spaces that may need tight temperature and relative humidity ranges. While most building systems can maintain a consistent upper limit of relative humidity (RH) throughout the laboratory, supplemental systems are needed to maintain minimum RH levels. If a facility only has one or two of these sensitive spaces, use local systems to maintain humidity levels. If the facility has multiple such spaces, grouping these in a suite can reduce the number of supplemental systems required, limiting both first cost and ongoing maintenance.

Occupant comfort varies based on operative temperature, air speed, relative humidity, metabolic rate (activity performed), clothing level, and exposure to direct sunlight. The Center for the Built Environment offers a thermal comfort tool to define an acceptable range of conditions for occupants based on ASHRAE Standard 55 – Thermal Environmental Conditions for Human Occupancy (Center for the Built Environment, n.d.). This tool can help clients and their project teams evaluate the acceptability of expanded environmental operating ranges for implementation in building systems (Figure 8).

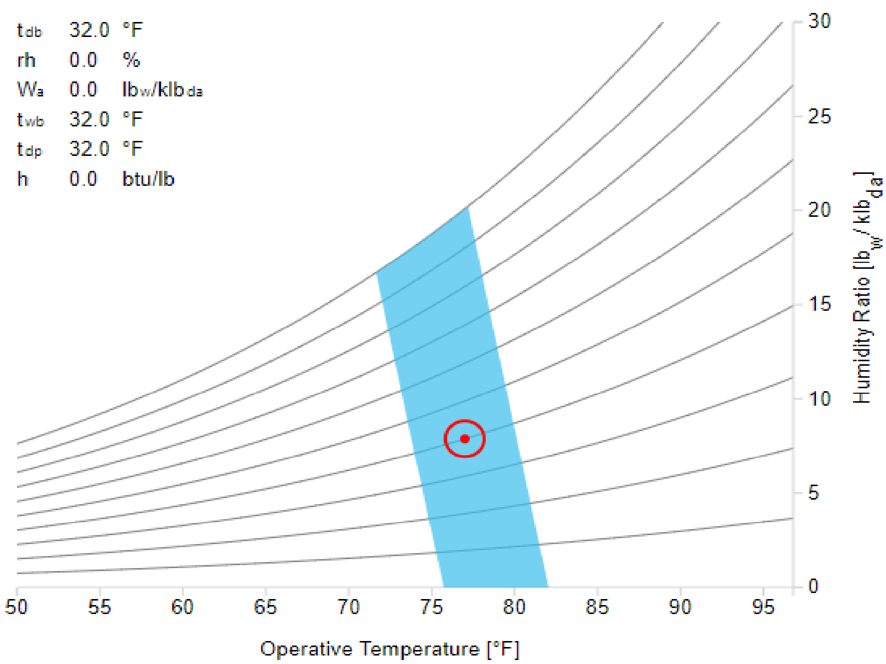


*Figure 8. Center for the Built Environment (CBE) comfort region output.*

### Maximizing Interaction of Lab and Office Programs

Designs should not be so focused on laboratory programs that they miss opportunities for increased energy efficiency in other areas. Daylighting, for example, can save energy in both offices and labs. Active chilled beams used to lower energy consumption in laboratory zones may also be applied to office spaces, providing a consistent mechanical systems infrastructure and similar energy savings.

Offices may also be complementary to laboratory programs. Building codes prohibit the recirculation of laboratory air beyond the space of origin, forcing single-pass airflow through laboratories. If laboratories are served independent of offices, then central laboratory systems become dedicated outside air systems (DOAS) with 100% outside air. If a separate supply air system serves adjacent office areas, building codes will require minimum ventilation for people for that system.

If, instead, these isolated programs are allowed by code to be combined into a common supply air system, the overall outside air ventilation may be reduced. While the need for laboratories to have single-pass supply air and exhaust does not change, the supply air from offices may continue to be recirculated. With this approach, laboratory ventilation required by the building code becomes a credit for people in the offices and may allow for ventilation to be reduced. The design ventilation rate of the common system then becomes the highest of either the laboratory or the ventilation rate for people and programs (office and laboratory). Most often, this results in an overall reduction of ventilation — and energy use — assuming the office areas, like the laboratories, are programmed to operate 24/7.

This approach is acceptable for most laboratory programs based on their classification. Refer to the Centers for Disease Control's Biosafety in Microbiological and Biomedical Laboratories (BMBL) for more information (Centers for Disease Control, 2020). This standard defines Biosafety Levels (BSL) for laboratories, together with criteria for design.

### Providing Mini-Environments for Energy-Intensive Processes

Like programs with narrow temperature and humidity ranges, energy-intensive programs may be consolidated or local systems provided to save energy. Energy-intensive programs include programs with high equipment loads, unusual process demands, or extreme environmental criteria, but may also extend to other programs, such as cleanrooms that require high volumes of HEPA-filtered air.

Consider a Good Manufacturing Process (GMP) pharmaceutical laboratory that requires a minimum ISO 8 (Class 100K) cleanroom for sample preparation and a limited amount of ISO 6 (Class 1K) cleanroom space for research. The ISO 6 cleanrooms will require more than 10 times as much HEPA-filtered air to limit particles as the ISO 8 cleanrooms. Instead of providing a single ISO 6 cleanroom to serve both preparation and research, a refined solution isolates the ISO 8 cleanroom from the ISO 6 cleanrooms to lower both first and operating costs. An enhanced solution may take this a step further, providing ISO 7 (Class 10K) research space with ISO 6 laminar flow hoods, potentially reducing both first and operating costs to achieve the same quality.

Similarly, a laboratory program may require a colder chilled water temperature or hotter heating water temperature for a specific process. Instead of designing the whole building to accommodate this localized program, supplemental systems may bridge the gap between central building systems and program requirements. This allows the central building systems to be optimized for the local climate and enhanced energy efficiency. Localized systems will likely be less efficient than central systems, but their smaller size and reduced need for distribution may negate any energy penalties.

## Planning Fume Hood Quantity, Size, and Location

As discussed above, minimum ventilation rates are determined by EHS officers for the health and safety of people in the lab. Fume hoods are containment devices (ventilated enclosures) used within laboratories to protect users from increased risks due to chemicals or processes. These hoods (and, in some labs, biosafety cabinets) provide the primary level of containment within the lab but can increase ventilation demand.

ANSI/AIHA/ASSE Standard Z9.5 establishes the minimum criteria for laboratory ventilation, laboratory containment devices, laboratory best practices, commissioning, and periodic testing (American National Standards Institute, 2012). For a fume hood or other containment device, the minimum ventilation rate with the device closed is based on a minimum range of air changes per hour (ACH) within the enclosure. Once a sash is opened, the ventilation rate increases in a hood with variable air volume (VAV) control, to maintain a minimum face velocity across the opening.

A typical fume hood with a vertical sash has an in-use sash opening of 18 inches with a design face velocity up to 100 feet per minute (FPM) based on EHS officer directives. While high-performance fume hoods may be safe at velocities down to 60 FPM, operation at this point is normally tested at ideal conditions with no drafts or people walking behind a researcher using a hood. As a result, most lab facilities operate closer to 80 to 100 FPM across the open sash area for increased safety. When fume hood(s) are placed in a room, the minimum ventilation rate for that room becomes the highest of either the minimum ventilation rate of the room or the minimum flow rate of the fume hoods.

Placing a large fume hood in a small room will drive the room ventilation rate up significantly. Where possible, select fume hood sizes and ventilation rates that are appropriate for the room size. In addition, the ideal fume hood placement limits staff from walking past hoods that are in use, since the wake of a person moving through air might compromise containment. Unless stricter isolation is required due to program needs or the use of hazardous chemicals, locating fume hoods in alcoves adjacent to open laboratories can minimize general lab ventilation, since the make-up air to the alcove can come from general laboratory ventilation, rather than new supply air from an air-handling unit directly to a hood in an enclosed room.

Beyond providing high-performance fume hoods with VAV control, and situating the hoods intelligently, the best strategy to lower fume hood energy use is to simply close the sash when hoods are not in use. With the sash closed, the ventilation rate for the fume hood drops to its lowest level, and the chemicals within are fully contained. This represents the best practice for fume hood use.

A sash closer is a device that can automatically close the fume hood sash when the user steps away after a preset time. Other approaches to limit fume hood ventilation utilize a zone presence sensor: a motion sensor that detects whether the hood is in use. When the fume hood is in use, the face velocity matches the criteria established by the EHS. When the user steps away, the face velocity can safely be lowered.

Some organizations have also seen success with “shut the sash” campaigns, aimed at encouraging lab users to practice good “hood hygiene” and manually shut sashes of hoods that are not being actively used. Again, an energy efficient lab is very much a team effort requiring a combination of approaches.

## Getting the Whole Building Right

In addition to these fundamental lab-centric principles, the strength of the overall building design can have a strong impact on the energy efficiency of the final project. As discussed in the box on page 6, facility design evolves from Planning and Programming through Schematic Design, Design Development, and Contract Documents, and early concepts turn into systems and building solutions. Design decisions will significantly affect both the project cost and the long-term energy performance. The best approaches bring together an integrated team early to implement the energy efficiency measures recommended in the Planning and Programming phase.

Important whole-building concepts for a design process maximizing energy efficiency include:

- Selection of experienced professionals
- Interaction of high-performance strategies
- Simplification of mechanical systems
- Separation of non-like functions
- Selection of adjacencies
- Deployment of daylighting and natural ventilation

### Choose Experienced Professionals

Laboratory programs can be energy-intensive and present unique challenges to maintaining necessary isolation from other building areas for safety and function. Building codes limit the type and amount of chemicals that can exist in a building based on number of floors above an egress level and the number of control zones. The complexity of mechanical systems and required laboratory process controls increase with the introduction of multiple control zones and tighter environmental parameters. Architects and engineers with exemplary experience in laboratory design, as well as a demonstrated sustainability track record, will work proactively in an integrated process to optimize design solutions.

### Maximize Interaction of High-Performance Strategies

Designing high-performance buildings requires a whole-building approach. A building with a tight, high-performance envelope but average mechanical systems will only perform slightly better than average. A high-performance mechanical system in a facility with an average envelope and poor shading will not be able to realize its full energy savings potential. As previously discussed, the design team should balance high-performance design within the available budget through detailed energy modeling and life cycle cost analysis.

Mechanical systems situated at one end of a building will require larger infrastructure and may force higher floor-to-floor heights and/or lower ceilings. Locating mechanical systems directly above laboratory spaces can optimize infrastructure with less impact to the building design but may require a more robust structural system for loading, vibration isolation, and sound isolation to minimize the impact to laboratory programs.

### Simplify Mechanical Systems Design and Distribution

Ideally, mechanical systems will maximize energy efficiency while minimizing complexity. Incorrect controls design or function can wipe out the anticipated energy savings of a potentially extremely efficient mechanical system. Systems complexity also needs to be consistent with facility staff's ability to maintain and operate the systems. Continuous energy monitoring and reporting can help keep systems operating efficiently and effectively (Rhoads, 2020).

Simplified systems distribution is also preferred as it can lower pressure drop and ease future modifications. An optimization of floor-to-floor and ceiling heights with architecture and planning will help alleviate any obstacles that may otherwise complicate the mechanical systems design. A common supply air system for office and laboratories allows flexibility for laboratory expansion in the future with laboratory exhaust nearby.

## Isolate Intensive and Non-Intensive Programs

While researchers may want to place office functions within laboratory zones, locating office areas in labs may limit staff access, put office staff at greater risk of exposure to chemicals, and increase energy use due to the larger laboratory footprint and the single-pass nature of ventilation in laboratories (based on classification). Instead, situating office functions outside of laboratory zones in nearby office areas allows office air to be "cascaded" into the lab zone, supplementing lab ventilation and reducing once-through lab air while protecting staff.

Having the researchers step outside of their laboratories for office functions also increases the potential for collaboration, since interaction with other researchers may trigger new and innovative approaches.

## Plan Adjacencies With Mechanical Systems

Laboratory containment is provided through containment devices, physical barriers, and pressurization. Pressurization requirements vary based on specific hazards and the relative risk to those outside of the laboratory. While some labs require positive pressurization to ensure cleanliness, most are maintained negative with respect to adjacent spaces to contain potentially hazardous conditions.

Understanding how airflows cascade from clean to dirty, from office to laboratory, can help limit the amount of transfer airflow needed to maintain negative laboratory pressurization. A laboratory suite adjacent to an open office area with an open corridor between allows office air to transfer to the laboratory suite, limiting the airflow needed for the corridor. If a corridor between an office and laboratory zone is enclosed for security reasons, transfer air ducts from the office to the laboratory might accomplish the same effect, provided all code-required rated exit corridors are duly respected and accommodated.

## Provide Daylighting and Natural Ventilation

The use of direct lighting is discouraged in lieu of indirect daylighting plus direct-indirect light fixtures. Reflecting light off interior surfaces such as ceilings or walls mimics daylighting and eases the transition from interior to perimeter daylit zones. Where focused light is needed, supplemental task lights can provide a suitable increase in light level.

While some research requires strict control of lighting, most staff will benefit from daylighting and the ability to look outside. The same logic applies to office areas.

The ideal building orientation to maximize daylighting is a bar shape, oriented on an east-west axis, with a narrow floorplate. Perimeter shading and fenestration design should limit sun angles and the potential for direct sunlight to impact work surfaces. Light shelves can direct light deeper into an interior space.

Natural ventilation is discouraged in laboratory spaces due to the inability to maintain uniform space temperatures and humidity, the presence of increased particulates, and the loss of pressurization control relative to non-laboratory zones. Natural ventilation is acceptable, however, for office areas independent from, or adjacent to, laboratory zones. ASHRAE 62.1 notes that, for a space to be considered naturally ventilated, the maximum distance to an operable window is 25 ft. A climate analysis is recommended before implementing a natural ventilation strategy to determine how much of the year natural ventilation can be utilized, as well as the potential cost savings.

The two types of natural ventilation are stack and crossflow ventilation. Stack ventilation allows air to enter through low windows along the perimeter, then naturally rise as it warms, to vent outward at a high point or via a stack. Crossflow ventilation uses perimeter windows on both sides to flush the space with natural breezes. The methods can be combined to increase their effectiveness. An office bar that is oriented east-west and is less than 50 feet wide has the potential to benefit from both daylighting and natural ventilation. (See Figure 9 for a good example.)

In the end, selecting more passive systems with a minimum of artificial ventilation saves energy.

*Figure 9. The National Renewable Energy Laboratory's Energy Systems Integration Facility (ESIF) office has a narrow east-west floor plan for daylighting, with prevailing winds from the north and south to maximize natural ventilation opportunities with operable windows. Source: Bill Timmerman, Timmerman Photography Inc.*

## Key HVAC Engineering Strategies

While improved mechanical systems efficiency often entails higher first costs, these costs may be offset by optimizations within other disciplines. Waiting until the program and floor plans are already established limits a project's ability to take advantage of these optimizations. Again, having the entire project team, including the MEP engineer, on board during Planning/Programming allows the best chance for implementing energy efficiency features.

Some key recommendations for building systems engineering, which dovetail with the lab-specific strategies previously discussed, include:

- Right-size building equipment
- Plan for part-load and variable operations
- Select premium high-efficiency equipment
- Implement low-pressure-drop design and water-based cooling
- Maximize any climate advantages
- Choose the right water temperatures
- Use direct digital controls and monitoring

### Right-Size Equipment

Engineers tend to oversize central systems to provide future flexibility and additional capacity for extreme events. Oversizing will result in higher first costs that may limit the ability to implement energy improvement strategies. Oversized equipment also does not turn down well and is difficult to control given significant operation at off-peak conditions.

Conversely, right-sizing matches the system sizing to the actual load profile. Right-sizing considers the concept of diversity — that not every laboratory and every space will operate at capacity at the same time on a design day. While smaller individual spaces are still sized for their design loads, large open labs are more subject to diversity. In open areas with many VAV fume hoods, the impact of diversity can be significant. Even though the large space will still be sized locally for the design condition, the building's central supply air and exhaust systems can take advantage of diversity.

### Plan for Part-Load and Variable Operation

Most buildings operate at their design point for only 1% of the year, yet equipment is often selected with only those design points in mind. Given the significant amount of hours that a building operates at off-peak conditions, consider a balanced approach to ensure optimum energy efficiency year round.

Another approach to achieve the same result considers the size and quantity of building mechanical equipment. With part-load operation, some equipment can be shut down such that the remaining equipment operates near its peak efficiency.

When evaluating chillers or other equipment for improved performance, consider the ability of the system to turn down to respond to variable loads. A highly efficient chiller with high minimum flows cannot turn down the pump flow and thus will waste pump energy year-round.

Pressure drop varies with the square of the velocity while power varies with the cube of the velocity. A 30% reduction in velocity when demand is low cuts the pressure drop associated with distribution in half and lowers the associated power by nearly two-thirds. Variable-speed systems take advantage of these opportunities to save energy. In laboratories, this not only lowers fan energy but also the energy required to condition ventilation.

### Select Premium High-Efficiency Equipment

Laboratories are energy-intensive compared with other building types, so energy investments will pay for themselves at a faster rate.

Select high-efficiency motors for fans and pumps that are rated for use with variable-frequency drives. The National Electrical Manufacturer's Association (NEMA) Standard MG 1 Part 31 defines characteristics for premium-efficiency motors used with VFDs (National Electrical Manufacturer's Association, 2019). For smaller systems, consider electronically commutated motors (ECM) that vary their output internally while maintaining a high energy efficiency. Look for ENERGY STAR labels certifying performance for motors and drives.

Modest increases in the size of supply air and exhaust systems will lower the face velocities of internal components (filters, coils, etc.). These reduced velocities in turn provide more contact time across surfaces for improved heat transfer, lower pressure drop, and reductions in fan energy and noise.

### Stress Low-Pressure-Drop Design and Hydronic Systems

After cooling and heating energy, the next largest energy consumer in laboratories is fans. Fan sizing is determined by the overall airflow capacity needed, together with the resistance of system components and distribution that needs to be overcome. While the overall airflow capacity is based on the building load or minimum ventilation rate, the pressure drop is based on the number of restrictions, extent of duct distribution, duct velocities, and pressure drops. Designing for low-pressure-drop HVAC systems includes the following:

- Reduced velocity in equipment (pressure drop varies with the square of the velocity)
- Reduced number of coils or obstructions within equipment to lower resistance
- Optimized duct distribution by minimizing fittings, using low-pressure-drop duct fittings, reduced velocities, and low-pressure-drop VAV airflow control devices
- Isolating or providing supplemental fan capacity for high-pressure devices to allow the overall system to operate at lower pressures and fan energy

For more specifics on low-pressure-drop design for labs, refer to Varley, 2020.

Like air-based HVAC systems, pump energy in hydronic (water-based) distribution systems varies based on flow and pressure drop. The combination of the high heat capacity and incompressible nature of water allow pumps to operate with considerably less energy while delivering the same amount of cooling or heating energy as air-based HVAC systems. Glycol (antifreeze) may be added to water to lower its freezing point, but its application also limits heat transfer and increases friction and pressure drop. Best practice limits the application of these glycol solutions so that the performance of the balance of the system is not impacted.

The application of active chilled beams in laboratories can lower ventilation rates to closer to minimum values (lowers energy to condition ventilation) while using the chilled and heating water systems to provide supplemental conditioning. The combination noticeably reduces fan energy, while the incremental increase in pump energy remains low.

### Maximize Any Climate Advantages

Mechanical systems design optimization starts with a climate analysis. Hourly weather analysis will help the design team understand the unique aspects of each location and select climate-appropriate solutions based on a typical year instead of just the design conditions for that site. A visual display of a year's worth of data (or more) allows the team to get a feel for seasonal conditions and assess the predominant operating conditions for the building.

Cooling designs in the dry western regions of the

United States can take advantage of evaporative cooling, using the evaporation of water in the air stream to cool the air. These same conditions allow cooling towers in chilled water systems to provide free or reduced-energy cooling as well.

In more humid climates, the use of enthalpy or desiccant recovery devices may assist in removing moisture from outside air. As previously discussed, use of wheels in lab facilities may be limited due to potential cross contamination.

For a common supply air system serving offices and laboratories in a humid climate, the use of a dedicated outside air system optimizes moisture removal while limiting overcooling and associated reheat. Energy-conserving design of laboratory HVAC systems should always minimize reheat. The use of a tempered or neutral air source for high ventilation for low-load programs has the potential to limit excess heating and optimizes performance.

In heating-dominated climates, waste heat recovery systems play a larger role. Runaround recovery systems use water-based (hydronic) systems to extract heat from laboratory exhaust to preheat ventilation at the supply air systems, with no potential for cross contamination. Given close proximity of supply and laboratory exhaust systems, refrigerant-based heat pipes can provide passive heat recovery with no pumps or cross contamination. Fixed-plate heat exchangers are another method of providing this recovery within a common supply and exhaust unit but need to be properly pressurized to protect against cross contamination. For this application, best practice places the supply fans ahead of, and the laboratory exhaust fans after, the fixed-plate recovery section, ensuring that any leakage in the common system is always from clean to dirty.

If a laboratory program in a predominantly heating climate has proximity to programs that require year-round cooling at a similar scale (such as a data center), the addition of a heat recovery chiller system is another approach to improving system efficiency. In the process of generating heat for the laboratory program during colder months, the heat recovery chiller system also provides beneficial cooling, offsetting cooling demands from other sources. Note that the efficiency of these systems depends on the system operating temperatures. Operation at cooler heating temperatures and warmer cooling temperatures can significantly improve efficiency.

### Choose the Right Water Temperature(s)

The hotter (or colder) the water temperature needed, the more energy that is expended to generate it. To improve energy performance, therefore, limit the amount of water needed for the most demanding temperature zones while meeting the needs of the remaining zones at a less demanding temperature.

Most hydronic heating and cooling systems are designed around a parallel circuit approach. In a parallel approach, the heating or cooling temperature is determined by the most demanding zone and is often reset seasonally based on outdoor conditions. With this method, all zones see the same fluid temperature regardless of their need. An alternative method is a series approach that isolates the most demanding temperature zones from the balance of the system to optimize energy performance. (Figure 10 on page 19 provides a graphic comparison.)

Consider a facility with a large process cooling water load (relative to the building HVAC load) that can operate at warmer supply temperatures to efficiently cool process loads and has matching water chemistry requirements to those of the building HVAC equipment. Instead of providing a common chilled water system to supply colder supply temperatures to meet both process and

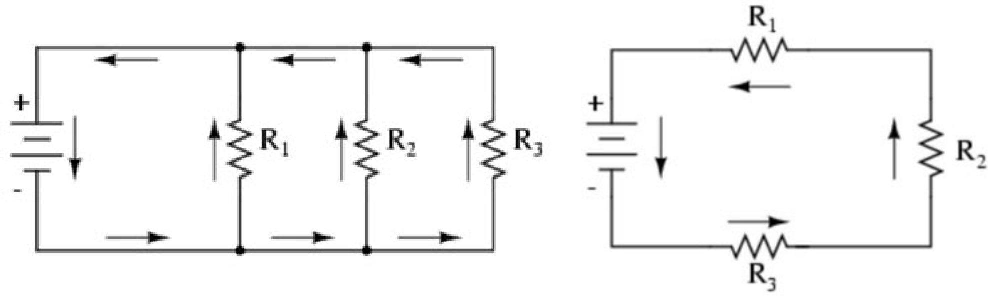


*Figure 10. Parallel (left) vs. series (right) electrical circuit correlation to hydronic heating and cooling systems. Source: EDinformatics, 1999.*

HVAC loads, the following approaches may improve energy efficiency:

1. Parallel approach. Instead of operating a single system to meet the most demanding condition, independent chilled water systems are optimized for their programs.
2. Series approach (process cooling water supply greater than chilled water return). This approach creates a secondary pumping loop from the primary chilled water loop, using chilled water return as the supply for process cooling water. The combined system increases the overall chilled water temperature differential and allows the chillers to operate more efficiently.
3. Series approach (process cooling water supply less than chilled water supply). This approach uses the primary chilled water system to provide the first stage of cooling, with a booster pump/chiller combination providing the balance of system cooling. By limiting the amount of cooling at the booster chiller, the overall building energy efficiency is increased, but system complexity and interdependence is also increased.

In another facility, a large, chilled water system for building HVAC loads also supports a small data center with hot aisle containment or active chilled beams. With hot aisle containment, the data center HVAC systems only need to supply slightly cooler room-temperature air to the server racks. Appropriately designed, these systems can operate efficiently with elevated chilled water temperatures approximating that of the chilled water return temperatures. Applying the second series approach mentioned above, the primary chillers generate supply temperatures based on the building HVAC demand. With the addition of secondary pump(s), the data center or active chilled beams then utilize chilled water return (with supplemental chilled water supply as needed) to cool their respective programs.

This combination improves overall chilled water energy efficiency by lowering pump energy and increasing chilled water temperature deltas, allowing the chillers to be more efficient. If smaller year-round chilled water systems are designed to match the data center or chilled beam supply temperatures, the entire system can then be reset upward, once the building HVAC system switches to free-cooling economizer mode.

## Incorporate DDC and Energy Monitoring Systems

An energy monitoring and control system (EMCS) that incorporates direct digital controls (DDC) is an essential element to the operation of an energy efficient laboratory. Unlike air-based pneumatic control systems or simple equipment-based controllers, an EMCS system with DDC can see the whole building operation, taking advantage of feedback from other systems to inform control decisions, notifying operators of anomalies, and automatically performing system diagnostics on a centralized computer network.

A properly designed, installed, and operated EMCS enables the efficient operation of buildings through monitoring, controlling, and tracking energy consumption. Large loads are monitored independently, and similar loads grouped accordingly to give the operator insight into the building energy use, such as electrical power, natural gas, HVAC loads, plug loads, lighting loads, and more.

EMCS scan also track and trend water usage (including process cooling, building systems, and irrigation usage) to inform water conservation measures.

## Power Choices for Efficient Buildings

Laboratories may find themselves limited by available power to support expansions and new programs. Time-of-day electrical demand charges may also cap the amount of power available within a given operating budget to support more laboratories. Both large and small projects can benefit from the application of distributed power technologies, which include, but are not limited to, on-site power generation and renewables.

### Investigate On-Site Power Generation

With time-of-day electrical rate schedules, utilities often include incentives to limit power demand during peak usage periods and reduce operating costs. Note that achieving this does not always require additional on-site power. A chilled water thermal or ice storage system, for example, can operate during off-peak power periods to store up cooling capacity and allow the chilled water system to operate at reduced levels during peak power periods.

Natural gas-fired generators and microturbines use natural gas to generate electricity. As natural gas is not subject to the time-of-day rate schedules, the use of these generators during peak power periods allows the building demand from the utility to remain low and take advantage of pricing incentives. In areas prone to electrical blackouts due to existing infrastructure challenges or limited capacity, these systems also help to stabilize operations and provide a level of redundancy and resilience for high-risk or mission critical programs.

Hydrogen or gas-fired fuel cells may also be useful in some situations for generating power on site.

### Consider Renewable Energy

Even though the energy efficiency of laboratories continues to improve, there is no expectation that most laboratories will become net zero energy facilities anytime soon. These facilities can, however, take advantage of renewable resources to provide positive benefits to the building.

Increasingly, renewable energy makes financial sense — though selection of potential technologies is sensitive to location, building orientation, program, and many other factors. Promising technologies for labs may include solar photovoltaic (PV), wind, and geothermal. Program limitations may impact the extent of energy efficiency that can be achieved, but renewable energy sources and/or purchases of green power should always be considered.

The price of solar photovoltaic modules has dropped by nearly 90% in the past two decades, and further price cuts are anticipated (Bloomberg, 2021). A PV system can be deployed over parking areas, providing shade for vehicles while simultaneously generating power for vehicle charging and overnight lighting of parking and pedestrian areas. The larger areas of roof typical in these facilities can also support the application of solar arrays.

Given the distributed nature of electricity, the solar arrays do not even need to be local to the building. Solar arrays can instead be located on another site or location where energy performance is improved, and installation costs are low.

Though large photovoltaic arrays may not be practical for areas with limited solar access, high-capacity evacuated solar tubes can provide for domestic, process, and building heating, with active heat-wheel regeneration offering an incremental advantage over passive regeneration for summer outside air dehumidification. Large deployments of these systems can also drive absorption chillers, using the heat of the sun to provide heating in winter and reduced-energy cooling in summer.

In locations where sustained winds are common, wind turbines become a power source to offset power demands. Other passive building strategies may be used to precondition ventilation for building HVAC systems, further lowering operating costs.

The use of geothermal systems in locations with more balanced climates engages the earth as a heat sink/source on an annual cycle to lower heating and cooling energy while reducing domestic water use in evaporative cooling. Geothermal systems may consist of horizontal or vertical networks, often located in parking lots or other open areas near the building. Either approach requires soil testing to validate the system size.

### Purchase Green Power

To augment their energy use, laboratories can opt to purchase "green power" from local utility providers. This green power supports the development of renewable energy resources, and typically comes in the form of hydropower, wind farms, or solar PV systems. Other technologies include concentrating-solar-thermal systems to heat and store salt solutions that continue to drive steam-powered electrical turbines even after the sun goes down.

## Commissioning, Operating, and Maintaining

Laboratory systems are complex and energy-intensive, and a commissioning provider plays a key role in ensuring their energy efficient operation. As a third party, independent from the design and construction teams, the commissioning provider advocates for the owner and helps the facility operators who will be charged with maintaining the efficient operation of the building systems.

Like the integrated design process, the best approach brings on the commissioning provider in the early stages, normally during Schematic Design after Programming and Planning is complete. Given their background and experience, commissioning providers' input to the design engineers streamlines operations, helps simplify control strategies, develops the appropriate procedures to test the systems, and provides early alerts regarding issues that are best solved before construction is complete and the building is occupied.

### Require Whole-Building Commissioning

The commissioning provider creates a design intent document complete with start-up and testing procedures for equipment and systems. During construction, the commissioning provider makes numerous visits to the site to ensure that systems are installed correctly and that control strategies in EMCS systems are fully implemented. Commissioning professionals also work with testing and balancing (TAB) professionals to ensure that the system performance meets the expectations of the project.

ASHRAE Guideline 0, The Commissioning Process, outlines the application of commissioning and includes the Total Building Commissioning Process

(TBCxP) as identified by the National Institute of Building Sciences (ASHRAE, 2019).

ASHRAE/IES Standard 202, Commissioning Process for Buildings and Systems, also offers guidance on the commissioning process and its implementation (ASHRAE, 2018).

### Benchmark, Monitor, and Report Annually

The benchmarking of peer facilities in similar climate regions provides a baseline by which the building can be compared (again, refer to the I$^2$SL Laboratory Benchmarking Tool). Historical data together with an appropriate breakdown of energy usage also acts as a benchmark for the facility looking into the future.

Annual energy monitoring and reporting verifies that building systems continue to operate as intended year after year. While occasional variations are to be expected, noticeable deviations can be identified, and corrective measures taken to restore system energy efficiency. Newly implemented energy conservation measures can also be validated through this process, and their operation optimized.

Over time, building owners may find that retro-commissioning (sometimes called “existing building commissioning”) may be helpful to identify important opportunities for better energy efficiency, including situations where systems have drifted from design values or where the building use has evolved so the prior design no longer works well. Many electrical utilities provide financial incentives for retro-commissioning, which aims to identify low- or no-cost, quick-payback strategies such as temperature and pressure resets, economizer modifications, and equipment scheduling. (See Mathew et al., 2021b, for details.)

## Conclusion

While laboratories have historically been high energy users, they represent one of the best opportunities for energy savings. As the Smart Labs program at UC Irvine has demonstrated, with the right focus and a concerted effort, it is possible to continue to grow laboratory programs while simultaneously lowering energy use. It begins with an early commitment from the team to pursue low-energy design, and the courage to continue to pursue energy-reduction opportunities throughout the design process and over the life of the building.

This publication does not attempt to address every energy challenge in every project. The variations in project size, program make-up, climate, resources, technology, and available budget create a large pool of solutions and possibilities. Instead, the goal of this Best Practice Guide is to open minds to the thought process of low-energy design, and to encourage all stakeholders to recognize the plethora of opportunities and resources available to enhance and improve energy performance.

As owners and designers experience success, we can share what we have learned with others in the community. In the act of sharing, our understanding increases, and challenges that once seemed insurmountable enter the realm of possibility. With every project we complete, we continue to move toward our goals of energy reduction and leaving a positive legacy for others.

## References

American National Standards Institute. (2012, April). *Laboratory ventilation* (ANSI/AIHA/ASSP Z9.5-2012). https://webstore.ansi.org/Standards/ASSE/ANSIAIHAASSEZ92012-1451471

Architecture 2030. (n.d.) *The 2030 challenge*. https://architecture2030.org/2030_challenges/2030-challenge/

ASHRAE. (2018, January). *Commissioning process for buildings and systems*. (ASHRAE/IES Standard 202-2018). https://www.techstreet.com/ashrae/standards/ashrae-202-2018?product_id=2025517

ASHRAE. (2019, July). *The commissioning process*. (ASHRAE Guideline 0-2019). https://www.ashrae.org/news/esociety/updated-commissioning-guideline

Bloomberg Finance. (2021). *BloombergNEF new energy outlook 2021*. https://about.bnef.com/new-energy-outlook/

Center for the Built Environment. (n.d.) CBE Thermal Comfort Tool. Retrieved 8.2.2021 from https://cbe.berkeley.edu/research/thermal-comfort-tool/

Centers for Disease Control. (2020, June). *Biosafety in microbiological and biomedical laboratories, 6th edition*. https://www.cdc.gov/labs/BMBL.html

Cochran, B.C. & Carter, J.J., (2021). *I²SL best practices guide: Designing and operating sustainable laboratory exhaust systems*. https://www.i2sl.org/documents/I²SLBestPractices_SustainableLaboratoryExhaustSystems_August2021.pdf

EDinformatics. 1999. *What is an electric circuit – series and parallel circuits*. Retrieved 8.2.2021 from https://www.edinformatics.com/math_science/what-is-an-electric-circuit.html

I²SL. (n.d.). Laboratory Benchmarking Tool. Retrieved 8.2.2021 from https://lbt.i2sl.org/

Mathew, P., Farmer, A., & Werner, J. (2021a.) *I²SL best practices guide: Benchmarking energy efficiency in laboratories*. https://www.i2sl.org/documents/toolkit/bp_benchmarking_2020.pdf

Mathew, P., Pierce, L., & Vitti, R. (2021b.) *I²SL best practices guide: Retro-commissioning laboratories for energy efficiency*. https://www.i2sl.org/elibrary/documents/I²SL_TechnicalBulletin_Retro-Commissioning_May2021.pdf

National Electrical Manufacturer's Association. (2019, March). *Motors and generators*. (ANSI/NEMA MG 1-2016). https://www.nema.org/standards/view/motors-and-generators

Rhoads, J. (2020, October). *I²SL best practices guide: Predictive maintenance using automatic fault detection and diagnostics*. https://www.i2sl.org/documents/toolkit/bp_predicitvemaintenance_2020.pdf

Smart Labs Toolkit. (2021). *A decade of Smart Labs experience: University of California, Irvine*. https://smartlabs.i2sl.org/cs-uci-sla.html Retrieved 7.26.21

U.S. Dept. of Energy. (2021). *Better Buildings Smart Labs Accelerator – Completed*. https://betterbuildingssolutioncenter.energy.gov/accelerators/smart-labs

U.S. Energy Information Administration. (1995). Commercial buildings energy consumption survey (CBECS). Retrieved 8.2.2021 from https://www.eia.gov/consumption/commercial/data/1995/

U.S. Energy Information Administration. (2019, April 16). *Today in energy*. https://www.eia.gov/todayinenergy/detail.php?id=39092

U.S. Energy Information Administration. (2020, April). *Monthly energy review*, (Table 2.1). https://www.eia.gov/totalenergy/data/monthly/archive/00352004.pdf

U.S. Environmental Protection Agency. (2018). ENERGY STAR Portfolio Manager technical reference: U.S. national energy use intensity. Retrieved 8.2.2021 from https://www.energystar.gov/buildings/tools-and-resources/portfolio-manager-technical-reference-us-national-energy-use-intensity

Van Geet, O., Walsh, M.J., & Reilly, S. (2012, June). *Laboratories for the 21st Century best practices: Energy recovery in laboratory facilities*. https://www.i2sl.org/documents/toolkit/bp_recovery_508.pdf

Varley, J. (2020, November). *I²SL best practices guide: Low-pressure-drop HVAC design for laboratories*. https://www.i2sl.org/documents/toolkit/bp_lowpressure_hvacdesign_2020.pdf

## Author

Robert Thompson, PE, SmithGroup

## Peer Reviewers

Otto Van Geet, PE, National Renewable Energy Laboratory

George Karidis, PE, SmithGroup

Hans Thummel, AIA, SmithGroup