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About the Cover

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The pursuit and practice of scientific research is traditionally a very energy- and resource-intensive process. Ironically, such work explores how to achieve more environmentally conscious living for all of society. In this issue’s Viewpoint, Evan Mills discusses how changes in computational and air handling infrastructures can make research facilities more sustainable. Notably, Mills comments about policies implemented at Lawrence Berkeley National Laboratory under its recent director Steven Chu, who was confirmed on January 20, 2009, by the U.S. Senate as the Secretary of Energy in the Obama Administration. Cover art by Rhonda Saunders using images from iStockPhoto. View the article.

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Environmental Science & Technology

Viewpoint

Sustainable Scientists

EVAN MILLS

Lawrence Berkeley National Laboratory

To make the practice of science more sustainable and cost effective, laboratories, equipment, and research infrastructures need to be designed and used with energy efficiency in mind.

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Scientists are front and center in quantifying and solving environmental problems. Yet, as a spate of recent news articles in scientific journals point out, much can be done to enhance sustainability *within* the scientific enterprise itself, particularly by trimming the energy use associated with research facilities and the equipment therein (*1–4*).

Sponsors of research unwittingly spend on the order of $10 billion each year for energy in the U.S. alone: the underlying inefficiencies drain funds from the research enterprise while causing 80 million tons of CO_2-equivalent greenhouse-gas emissions (see Box 1). These are significant sums considering the amount of additional research that could be funded and emissions that could be reduced if the requisite energy were used more efficiently. By following commercially proven best practices in facility design and operation, scientists—and the sponsors of science—can efficaciously halve these costs and so do their part to put society on a low-carbon diet.

Improving energy productivity is a doubly worthy challenge, given that those making the biggest contributions to the science of sustainability often do so in highly energy-intensive facilities such as laboratories, computing centers, and hyper-clean environments. There is a long way to go to meet the sustainable practices. According to a U.K. Department for Environment, Food, and Rural Affairs survey, virtually all interviewed scientists view their field as an important factor in developing sustainable solutions. Only 40% of those surveyed reported having "always" or often considered the effect that their work would have on the environment (*1*). It has been estimated that a mere ~1−3% of laboratories are "green" (*4*).

Given that today's scientific facilities can be more than 100 times more energy-intensive than conventional buildings, measured in terms of energy use per unit of floor area (Figure 1), energy use is probably the single most important contributor to these facilities' overall environmental footprint (*6–8, 14*). Particularly high energy usage can be found in extreme climates: hot and humid areas in the developing world are seeing strong growth in these types of facilities. A recent gathering in India highlighted the particular issues and opportunities there and resulted in the initiation of new activities focused on training and diffusing best practices (*15*).

Improvements in efficiency are increasingly being driven by a desire to save money and lessen environmental impacts. Various federal, state, and local mandates are also spurring improvements. Examples in the U.S. include local building codes affecting privately owned facilities; mandatory national targets for government-operated facilities stipulated by a series of Executive Orders; and incentives and training as called for in the Energy Policy Act of 1992.

Inefficiencies Exact a High Opportunity Cost for the Scientific Enterprise

Energy costs in research facilities can be staggering, e.g., electricity demand at the CERN site is 230 MW, or $80 million each year assuming 270 days of operation (*16*) (see Box 1 for an explanation of the price estimations used herein). High-performance computing centers throughout the U.S. Department of Energy (DOE) system incur aggregate energy costs on the order of $100 million per year, a number that is rising rapidly with increasing demands for computing power. Oak Ridge National Laboratory is looking at scenarios of nearly 70 MW in power demand for new scientific computing facilities and associated cooling infrastructure within the next few years (*17*). This corresponds to about $60 million per year in electricity costs for that one site alone. Other supercomputers on the drawing board will demand well over 100 MW each. For comparison, a large central-station electric power plant produces 600 MW of power, enough for about 250,000 typical U.S. homes.

The good news is that the potential to trim these costs is dramatic. Energy savings in high-tech facilities on the order of 50% are readily achieved (*13*) through an integrated effort by the following: researchers; those who fund research, including the construction and operation of scientific facilities; and the architects and engineers who design and build research (infra)structures. Between 1977 and 1994, $47 million was invested in energy studies and $290 million was invested in 1100 retrofit projects at DOE facilities across the U.S., with an average payback time of 3 years (*18*). This yielded annual savings of $100 million (in 1994 dollars) and a return on investment in excess of 25%. Through these efforts, DOE cost-effectively reduced its nationwide facility energy intensity by 43% and those efforts have continued. In 2008

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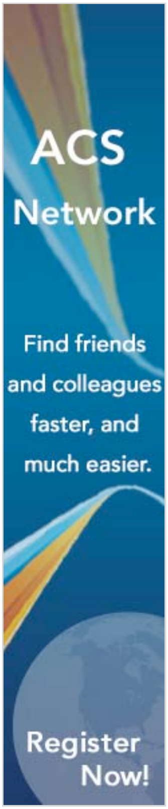

Box 1: Scoping U.S. R&D facilities' $10 billion energy bill

There is no official estimate of energy use in research facilities. National surveys such as those conducted by the U.S. Department of Energy (DOE) (*5*) do not separately evaluate research facilities. Here I present a rough scoping estimate for private- and public-sector research facilities in the U.S. based on available information, and 12-month rolling-average commercial energy prices of $0.1010/kWh for electricity and $11.47/GJ for fuel, as of September 2008. These values are used for all cost estimates developed in this article unless otherwise noted.

Laboratories. Prior work indicates an expenditure of $4.2 billion per year for U.S. laboratory fume hoods (for direct fan energy as well as associated space-conditioning energy), as of 2004, based on bottom-up modeling (*6*), or $5.2 billion today. This is combined with $2.1 billion for laboratory plug loads and lighting per the end-use breakdowns from the EPA/DOE Laboratories for the 21st Century benchmarking database, which indicate that 29% of total laboratory energy is attributable to these end uses (*7*).

Computing. A detailed estimate places total electricity consumption for U.S. servers and data centers at 61 TWh as of 2006 (*8*), including energy used directly by the IT equipment and associated space-conditioning systems. This translates to $6.2 billion per year. The portion attributable to the research applications is $1.2 billion, based on an assumed 20% fraction.

Included in this value are U.S. supercomputing sites: of these, 157 out of 290 collectively reported through the "Top500" project ~69 MW in measured demand for computing alone, equivalent to $110 million annual energy expenditures, including associated space-conditioning (*9*).

Clean environments. In the absence of any prior estimates, I refer to the estimated ratio of cleanroom to laboratory-type facility energy of 1.4 for California (*10*), and scale this value to the U.S. This generates an estimate of $7.2 billion per year for all cleanrooms. The portion attributable to research applications is $1.4 billion, based on an assumed 20% fraction.

The sum of these estimates forms the basis of our conclusion that energy-use for high-tech research facilities in the U.S. is on the order of $10 billion. Assuming national-average emissions factors for CO_2 equivalents of 0.959 kg/kWh electricity and 50.3 kg/GJ for natural gas, the energy use corresponds to approximately 80 Mt of CO_2-equivalent greenhouse gas emissions each year. According to multipliers provided by the EPA (*11*), these emissions are comparable to those from:

- 7 million U.S. homes;
- 15 million U.S. passenger cars;
- 420,000 rail cars of coal; or
- 17 coal-fired power plants.

Due to the absence of data, these estimates do not include transportation energy use associated with research facilities (or related travel) or the energy for desktop computing. Nor are specialized facilities such as particle accelerators, electron microscopes, and/or medical equipment included. For an indication of these facilities' cost, one example is the energy expenditures in "energy-intensive" U.S. federal facilities, which was estimated at $900 million in 2005 (*12*).

Given the magnitude of the result, a more detailed analysis is clearly warranted and would presumably be of strategic value to those funding the R&D enterprise as well as individual scientists trying to accomplish the maximum amount of work within a constrained budget.

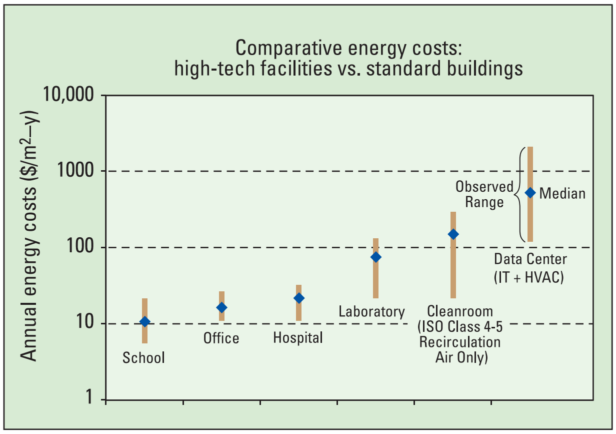

FIGURE 1. Range of measured energy intensities in high-tech facilities. Schools and offices are shown for comparison. Adapted and updated from ref (*13*).

alone, new energy-savings projects were initiated at four DOE national laboratory sites with projected combined savings of $13 million per year (*19*).

Lawrence Berkeley National Laboratory's (LBNL's) recently constructed Molecular Foundry, which contains laboratory, computing, and cleanroom spaces, provides an example in which substantial savings were achieved compared to typical practice yet with no net increase in construction costs (Figure 2) (*20*). The Molecular Foundry is an example of the emphasis on sustainable research practices that has been of central importance to LBNL's Director Steven Chu since he became the Laboratory's Director in 2004. Dr. Chu's work at LBNL contributed to his being picked as the nominee for Secretary of Energy by President-Elect Barack Obama in December 2008 (*21*). In the case of retrofitting existing buildings, there are usually net costs, but the investments are quite cost-effective. For example, energy upgrades at 36 computing facilities around the U.S. yielded a median payback time of three years (*13*). Many measures, particularly those associated with improved operations and maintenance, pay for themselves in a matter of weeks or months.

Improving Productivity and Safety Through Increased Energy Efficiency

"Doing the right thing" isn't the only reason to strive for improved sustainability. The scientific enterprise depends on availability of ample energy and can be fettered by its cost. In the 1980s, LBNL's particle accelerators were responsible for the vast majority of site-wide energy use. Indeed the Bevatron's energy budget only allowed for ten months of experiments each year. At the time, raising the energy-efficiency of the process (e.g., through improved magnets and power supplies) trimmed consumption and costs sufficiently to enable a full year of experiments to be conducted.

Albeit less sensational than large "big science" facilities, synthesis and theory laboratories can also constrain research via their inefficient use of energy. As air-hungry fume hoods

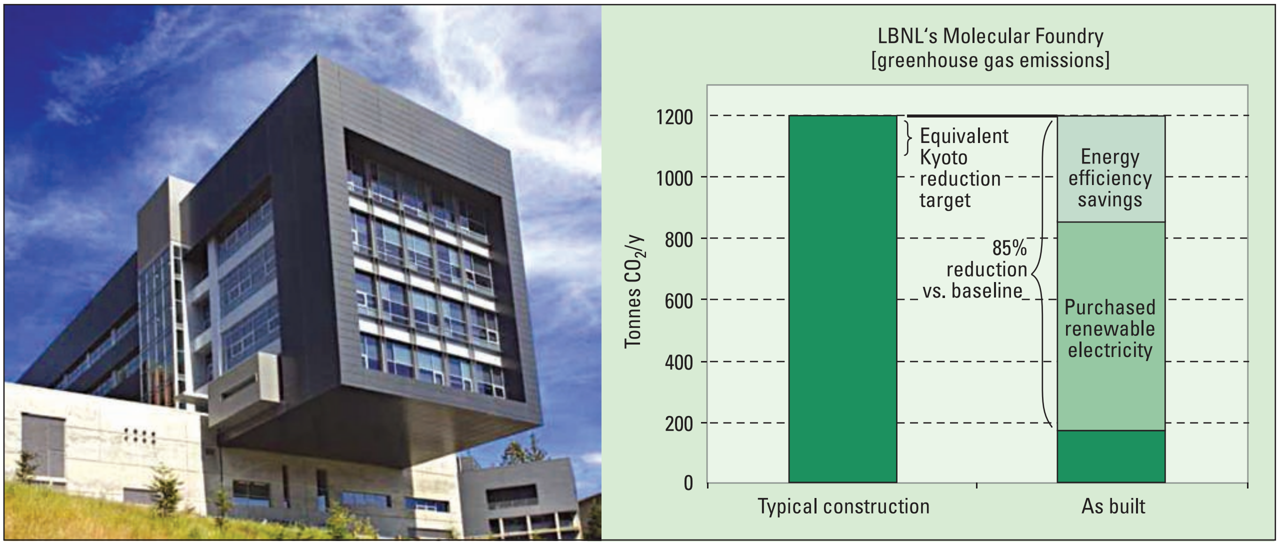

FIGURE 2. The Molecular Foundry nanotechnology research facility at LBNL achieved a Leadership in Energy and Environmental Design (LEED) Gold Rating, thanks to extensive green and energy-efficient features and renewable power purchases (*20*). Estimated CO_2 emissions are 85% less than standard practice, which includes aggressive environmentally conscious California building codes. This puts the Molecular Foundry vastly ahead of the national average for percentage reductions in CO_2 called for by the Kyoto Protocol.

are added to laboratories, the facilities can become starved for air once the aggregate flow exceeds the design capacity. Many laboratories could support more hoods, and thus afford more research output, if energy efficiency is improved in ways that safely reduce the flow and associated fan energy. Similarly, computing facilities are increasingly vexed by insufficient power infrastructure or excessive heat production, both of which can put *de facto* limits on computational capacity and jeopardize reliability (*22*).

Enhanced energy efficiency can also be a friend of safety, rather than compromising it as folk wisdom often implies. For example, by maintaining a relatively constant velocity of airflow into the hood opening, variable-air-volume (VAV) fume hoods dramatically lower energy use while reducing turbulence and thereby enhancing hood containment. VAV controls generally incorporate monitoring and alarming functions that also improve safety.

The Power of a Systems Perspective in Design and Operation

The potential for energy savings is routinely affirmed by benchmarking investigations that reveal energy intensity variations of a factor of 5 or more for facilities supporting similar activities and providing similar or greater levels of services, reliability, comfort, and safety (*13*) (Figure 1). Particularly significant gains and savings in up-front construction as well as ongoing operating costs can be achieved by optimizing high-tech facilities at the systems level, not just individual pieces of equipment. The combined effect of multiplicative inefficiencies is well demonstrated in the case of data centers. As shown in Figure 3, overall system efficiencies range from 12% for poor practice to 60% for best practices. Beyond the impact of component efficiencies, overestimates of process loads, redundant and uncoordinated "safety margins", and unoptimized control equipment and algorithms all conspire to produce facilities that use more energy than necessary. Fully involving owners, occupants, and service providers in the articulation of "design intent" and establishing performance goals and metrics improves the likelihood of a successful outcome (*23*). A focused operations and maintenance program helps to ensure performance over time.

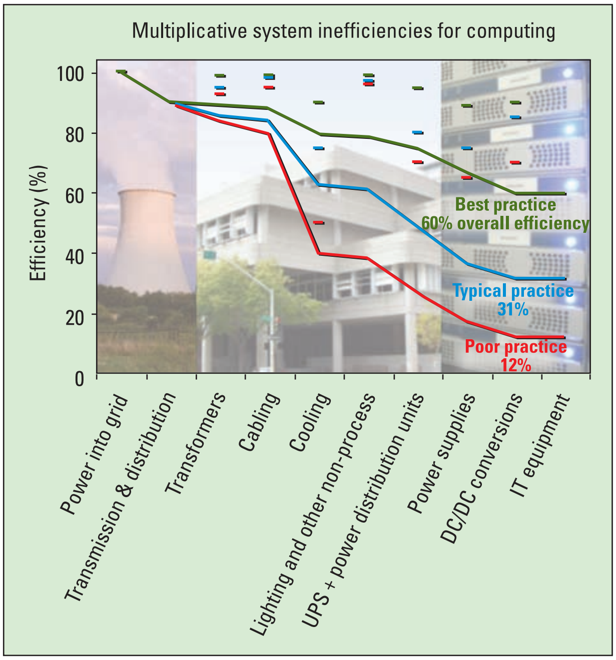

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FIGURE 3. Individual (dashes) and cumulative (curves) efficiencies of data center systems. The system boundary shown here does not include "upstream" efficiencies in power generation (~35%), or downstream and parasitic energy losses or opportunities within the IT equipment itself (e.g., cooling fans or virtualization).

Dependency on rules-of-thumb during design is a pervasive problem that routinely leads to an overestimation of energy needs resulting in wasteful capital expenditures for ongoing expenses due to inefficient operations (*24*). Unnecessary simultaneous heating and cooling is also commonplace and can be cost-effectively remedied. Selecting premium efficiency equipment is as important for energy-cost savings as improving air-movement and space-conditioning infrastructure. Choices that can make an impact are not limited to lighting, fume hoods, computers, refrigeration units, or process devices. To wit, efficient process equipment imposes smaller loads on central space-conditioning systems, but this benefit is often overlooked by infrastructure designers.

Better facility management and rethinking the underlying processes can also yield considerable savings. According to a study by the American Chemical Society Green Chemistry Institute, colleges and universities are looking at ways to adjust their curriculum so as to require fewer hoods by reducing the use of volatile organic compounds and/or including hood-free experiments (*25*). For example, the University of Oregon saved $250,000 in one-time capital costs for fume hoods and $87,000 annually in associated energy. St. Olaf College cut the number of hoods needed in a new facility by nearly half, and the Massachusetts Institute of Technology (MIT) has established a program that automatically records night-time sash positions and reports the information back to the research group so as to optimize for forward energy efficiency.

Laboratories

As an indication of the efficiency opportunities in facilities, detailed benchmarking results of actual laboratories show an 8-fold variation in energy intensity (*13*). The main categories of energy-saving measures include specifying premium-efficiency fume hoods and laboratory equipment (*26*), avoiding overventilation, minimizing pressure drop in the ventilation system, energy recovery, minimizing simultaneous heating and cooling, and properly sizing space-conditioning equipment to match actual loads.

Ventilation systems, including fume hoods, are the dominant energy drains within laboratories. A single average fume hood in the U.S. consumes approximately 35 MWh of electricity and 275 GJ of fuel or $8000/year (including direct ventilation energy and the energy associated with conditioning the air) (*6*). Given more extreme climates, the operating cost for the same hoods in Singapore or Fairbanks would be about $12,000/year (Figure 4). High-performance hoods can reduce these values by 75% (*6*).

However, while fume hoods represent the single greatest energy-saving opportunity in laboratories, the appropriate strategy is context-dependent (*27*). For example, where hood density is low and hoods are not the primary source of general laboratory ventilation, using bypass hoods rather than VAV hoods is simpler and just as efficient.

It is not enough to have a well-designed facility; occupants often must participate by activating energy-efficient features. For example, one study found a 66% savings potential for improved fume hood sash management (*28*), without even changing the equipment to higher-performance hoods. The associated sash-management savings potential in MIT chemistry laboratories was estimated to be $350,000 per year. In addition, while infrastructure decisions (building envelope and ventilation) are typically not in the direct control of researchers, the specification and purchase of energy-efficient laboratory equipment is something that they can influence.

Computing

As many forms of research move from the benchtop to the computer, high-performance computing is overtaking accelerators and other energy-intensive processes as the primary electric load at many research facilities. Computing energy-intensity has become so significant that the up-front capital cost of power and cooling infrastructure routinely exceeds that of the information technology (IT) equipment itself (*29*). Energy requirements for the fastest next-generation facilities could rise sharply. As a proxy for this, computing power for high-resolution climate models is expected to increase on the order of 1000-fold from current levels (*30*). A recent DOE report contemplates an exaflop (Eflops; EFLOPS) high-performance computing system requiring over 130 MW of power (*31*). The business-as-usual scenario implies emissions of 700,000 tons of CO_2 annually and an annual energy bill of $114 million for this single facility. The potential to achieve the same performance at high-efficiency could require as little as 20 MW of power. Other scientific computing applications will not likely present the need for such increases in computing power, but still have a large scope for improved efficiency.

The prodigious use of computing power translates into an untenable need for air-conditioning capacity. Indeed, the values for the DOE study above do not include cooling, which could double the cost. The energy and environmental price tag aside, a recent survey found that 42% of conventional data centers expect to run out of cooling capacity within 1−2 years (*32*). Benchmarking results for computing sites in the U.S. show that the fraction of total power going to computing itself ranges from 30% to 75%, a reflection of inefficient space-conditioning systems. The University of California's planned Computational Research and Theory (CRT) Facility is aiming for a target of 83%, which implies a highly efficient cooling strategy. To put this in context, the adjacent LBNL Campus currently has a 13 MW electricity demand, which would have nearly quadrupled with the initially proposed 35 MW CRT. The current goal is containing the ultimate size of the CRT to 17 MW, corresponding to a $16 million annual reduction in energy costs compared to the initial plan.

The "Top500" list benchmarks the power consumption and efficiency of the world's 500 largest supercomputers (*9*). As of 2008, the average power efficiency of 122 Mflops/W is a quarter of the best at 488 Mflops/W. Some of the fastest machines on the list are also the most efficient. Improved analytics are needed in order to properly rate and rank supercomputing systems' energy performance.

Efficiency opportunities for computing facilities include improved IT equipment, (uninterruptible) power supplies, and more efficient cooling strategies (Figure 3). Computational efficiency can also be improved, and underutilized machines can be consolidated and virtualized. Fundamental process changes can also be implemented, such as shifting to a direct-current infrastructure that in one demonstration project yielded a 10% facility-wide savings compared to the best-available AC configuration, and more than 25% compared to conventional practice (*33*). Pilot projects have already demonstrated this technology in the U.S., Germany, and Japan.

Deeper savings can be achieved with fundamental computational architecture changes reflected in current conceptual designs for low-power, application-driven, semicustom embedded processors (*34*). If successful, energy savings for a single next-generation climate-modeling facility for a task such as 1.5 km resolution climate modeling would top $1 billion per year (*35*). Systems such as this, coupled with renewable power supplies, could go so far as to achieve full carbon neutrality. Ironically, these same facilities would improve the ability to simulate anthropogenic climate change.

Clean Environments

Clean environments are widely embedded in research facilities, ranging from those for biotechnology to optics to semiconductors (*36*). With up to several hundred air-changes each hour, these are among the most energy-intensive of high-tech environments.

A comparison of eight ISO Class-5 cleanrooms in the U.S. found a nearly $400,000 per year (8-fold) variation in floor-area-normalized ventilation energy costs. In ranging from $25 to $215/m^2-year, this is another indication of significant energy-efficiency opportunities (*13*).

In clean environments, priority should be placed on premium-efficiency air-movement equipment and design,

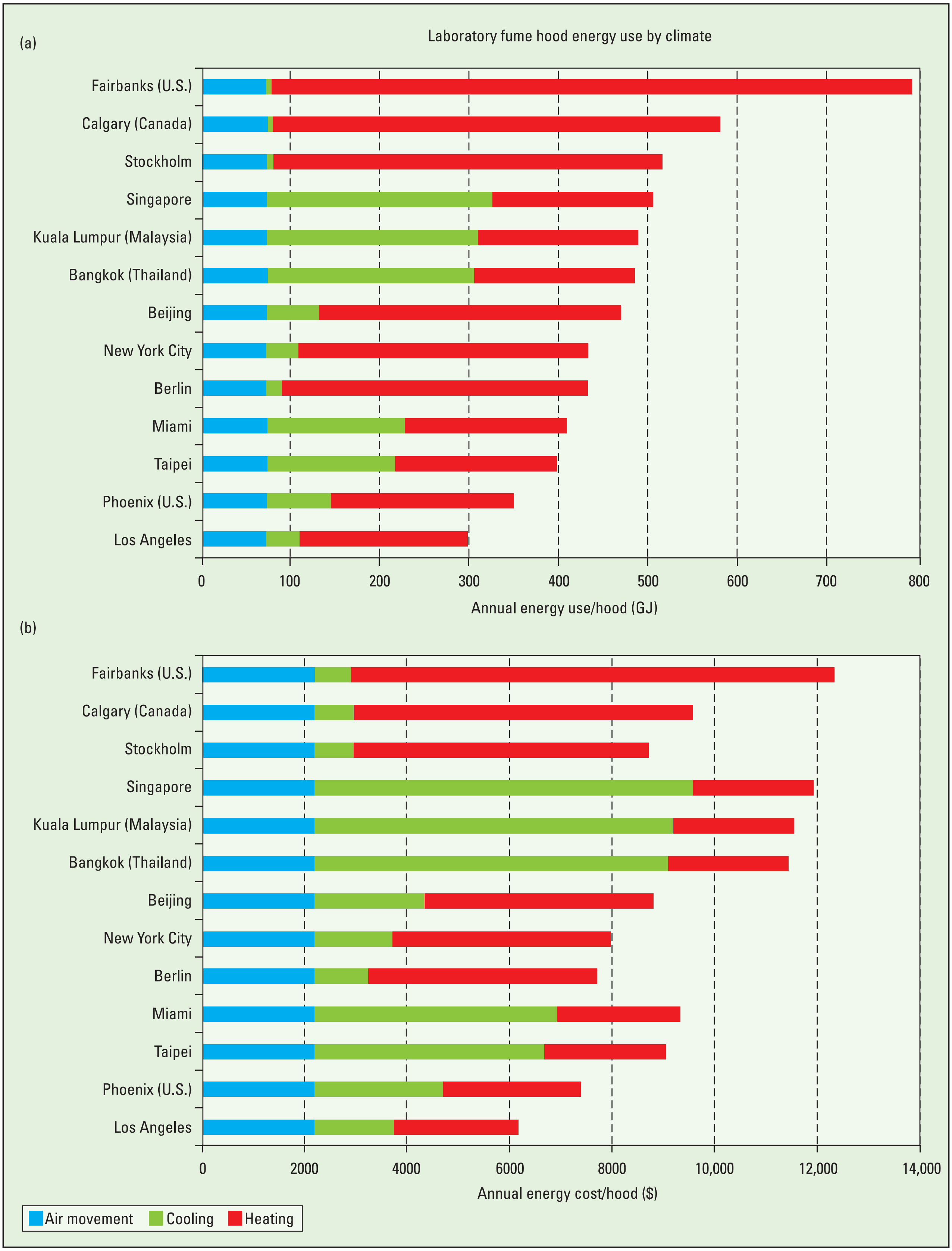

FIGURE 4. Energy use and operating costs for laboratory fume hoods in differing climates. Adapted with permission from ref (*6*).

as well as more efficient tools and process equipment. As in other high-tech facilities, process changes can also yield savings. For example, mini-clean environments can isolate the sensitive process to a small and more easily controlled space. This further allows for relaxed particle-count limits in the surrounding space and by reducing air movement costs incurs good energy savings (*37*). Also, rules-of-thumb for design air-change rates (ACH) may not be well-founded: benchmarking analyses show a 6-fold variation among "identical" ISO Class-5 cleanrooms (100−600 ACH). That of the facilities benchmarked, half were operating below the lower range of typical practice (250 ACH) shows that great progress can be made by attending to a few especially energy-intensive facilities (*13*). Real-time particle counting can be used to modulate ventilation speeds, thereby better managing energy demand (*38*). Expanded-area filtering can save energy by reducing pressure-drop and trim waste and maintenance costs thanks to less frequent replacement needs.

Toward Best Practices

Scores of specific energy efficiency measures can be applied in research facilities. To provide context and coordination, an overall sustainable-science energy strategy can be structured as follows:

- Institute an enterprise-level energy management program integrated with other functions (risk management, cost control, quality assurance, employee recognition).
- Involve all key stakeholders early in design process: keep the team focused on common goals; clarify and document the rationale for key design decisions supported by energy use and performance benchmarks.
- Apply life-cycle cost analysis to purchasing and decision-making, including nonenergy benefits (e.g., reliability and environmental impacts).
- Avoid excessive/redundant “safety margins” by using right-sizing to trim initial costs.
- Include integrated performance monitoring controls in the design and incorporate the information gained into operations and maintenance and an ongoing process of opportunity assessment.
- Incorporate a comprehensive quality assurance process (often called “commissioning” or “retro-commissioning”) into new construction and renovation to detect and correct physical deficiencies that erode savings and/or performance, as has been cost-effectively demonstrated at University of California (UC)/California State University (CSU) laboratories (*39*).
- Provide facility operations staff and researchers with site-specific training to minimize energy usage.

The challenge is as much institutional as it is technical. As an illustration, of 27 UC Santa Barbara laboratories offered an unsolicited no-cost assessment of their energy opportunities in 2007, only 4 accepted (*3*). There are often split incentives when the researchers who stand to use energy more efficiently do not make capital investment decisions or pay the bills. Meanwhile, few if any sponsors of research consider energy efficiency as a criterion in evaluating grant proposals or grantee financial management.

In this, the ultimate agents of change are the scientists occupying research facilities. While scientists cannot optimize sustainability without institutional support, they can provide the catalyst and convene otherwise fragmented parties in the process (e.g., research sponsors, architects, and engineers). Be it weighing in during the design of a new facility, selecting equipment, or retrofitting and operating an existing facility more optimally, sustainable facilities require sustainability-minded scientists along with technicians, students, and support staff.

Incentives and Other Deployment Initiatives

As facility designers and energy managers achieve relative mastery of “ordinary” energy-saving technologies for homes and businesses, energy-efficiency research and deployment initiatives are expanding their horizons to include “high-tech” scientific facilities and processes.

There are many resources and programs to assist motivated research institutions. Particularly notable public-sector initiatives are DOE’s Industrial Technologies Program (ITP), EPA and DOE’s Laboratories for the 21st Century initiative (Labs21), the California Energy Commission’s Public Interest Energy Research Program (PIER), and a variety of research projects sponsored by the New York State Energy Research and Development Authority.

Meanwhile, energy utilities are beginning to offer rebates and other financial incentives to help high-tech customers implement and fund energy-efficiency upgrades. For example, the Utility IT Energy Efficiency Coalition, with 24 member utilities led by Pacific Gas and Electric Company, is developing consistent energy efficiency program and service offerings for improving computing energy efficiency.

Laboratories are participating in the Leadership in Energy and Environmental Design (LEED) program for rating energy efficiency and other sustainability features. Additionally, LEED-like protocols for laboratories have been developed and similar processes are being assessed for computing and clean environments. The National Renewable Energy Laboratory’s Science and Technology Facility, and laboratories at UC Santa Barbara and UC Davis have received the highest LEED rating (“Platinum”) while saving about $90,000/year in energy costs and significantly improving the working environment (*4*). LBNL’s Molecular Foundry (Figure 1) received LEED’s “Gold” rating.

Industry is also taking initiative. IT manufacturers have formed the Green Grid alliance to address efficiency and sustainability issues (*40*). This group is exploring energy efficiency opportunities in servers and data centers, including standards, measurement methods, and new processes and technologies. The semiconductor industry is also developing process equipment energy efficiency improvement programs (*41*) and their Green Fab initiative is modeled on the Labs21 and LEED programs (*42*).

By leveraging these initiatives, the sponsors of research—who ultimately pay the energy bills—could benefit from promoting energy efficiency in the facilities where the work they fund is performed. One place to start would be to introduce energy efficiency criteria into the process of soliciting and evaluating research proposals. If capital expenditures are part of a proposal, funding recipients could be encouraged or even required to purchase premium-efficiency equipment and optimize their facilities for minimum life-cycle cost and reduced greenhouse-gas emissions. As in all things, improving the sustainability of science must be a group effort.

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