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The business case for energy management in high-tech industries

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Abstract The high-technology sector – characterized by facilities such as laboratories, cleanrooms, and data centers – is often where innovation first occurs. These facilities are sometimes referred to as the "racecars" of the buildings sector because new technologies and strategies to increase performance often trickle down to other building types. Although these facilities are up to 100 times as energy-intensive as conventional buildings, highly cost-effective energy efficiency opportunities are often overlooked. Facility engineers are in the trenches identifying opportunities to improve energy productivity but often are unable to make the broader business case to financial decision makers. This article presents the technical opportunities for reducing energy costs, along with their broader strategic value for high-tech industries.

Keywords Energy efficiency · Laboratories · Cleanrooms · Data centers · Non-energy benefits · Green buildings · Decision-making

Context

The USA spent about $850 billion on energy in 2005; global energy expenditures are no doubt several times

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as great. As energy prices continue to escalate, the overall impact on business energy consumption will deeply affect the world's economies.

Huge strides have been made in energy efficiency since the 1970s, contributing – along with structural and behavioral changes – to a decline in energy intensity (as measured in energy used per unit of activity) in most nations. In the case of the USA, energy intensity fell by almost 50%. Many of these efforts were carried out in conventional commercial buildings, particularly office buildings, with very little emphasis on high-performance buildings including high-tech operations, i.e., laboratories, cleanrooms, and data centers. Rather, in the race to apply new technologies in high-tech facilities, much emphasis has been placed on improving service, building capacity, and increasing performance. With a singular focus on throughput, important design issues can be overlooked, such as the energy efficiency of individual pieces of equipment (e.g., lasers, fans, routers, and switches) and the integration of high-tech equipment into the facility's power distribution system and the building envelope.

High-tech facilities are socially and economically important as part of the critical infrastructure for pharmaceuticals, electronics, communications, and many other sectors. With increasing amounts of economic activity dependent upon products and services manufactured or delivered through high-tech buildings, a renewed focus on improving their energy efficiency is warranted. Similarly, concerns regarding short and long-term energy availability and security have become strategically important to the high-tech sector. Because of their relatively high energy intensity, high-tech facilities are at once vulnerable to price fluctuations and, at the same time, ideally poised to achieve dramatic energy efficiency improvements.

In turn, efficiency improvements translate not only into operating cost savings but also into improved product and service quality, competitive advantage, and increased earnings per share. Among the examples highlighted in "Energy efficiency is the tip of the iceberg" of this article are improved control of cleanroom processes and ventilation speed through the use of real-time particle monitoring, improved working conditions in laboratories and other facilities through better management of indoor air quality, and improved reliability in data centers and other high-tech facility types – thanks to more effective and efficient infrastructure.

Among technology-based businesses, improving energy efficiency presents an often-untapped opportunity to increase profits, enhance process control, maximize asset value, improve the workplace environment, and manage a variety of business risks. Oddly enough, until recently, the adoption of energy efficiency improvements in this sector lags behind many others. As a result, billions of dollars are left on the table with each year of operation.

Energy inefficiency reflects organizational inefficiency. In the case of the high-tech sector, facility engineers are in the trenches identifying opportunities to improve energy productivity. However, conflicting priorities involving the use of capital often pit short-term revenue generation technologies against those technologies that support infrastructure and energy use that may result in longer-term payoff periods. Even in technically sophisticated organizations, this prioritization of the short-term often results in the neglect of facilities and energy infrastructure, which, in turn, leads to wasteful and unnecessary operating expenses over the long-term. A virtual cultural divide between engineers and corporate decision makers can leave promising efficiency upgrade projects to die on the vine.

Staying on the cutting edge in one's core business requires maximizing energy productivity. Because industries that have high-tech facilities require particularly energy-intensive buildings that run 24 h per day, 7 days per week (24×7), energy-efficient design, and operation provides significant leverage to reduce overall operating costs. At the extreme, cleanrooms and high-density data centers can use up to 100 times as much energy per square foot as a typical office building (Fig. 1), often spending more than $1 million per month on energy.[1] Taken in aggregate, worldwide electricity use for servers alone is equivalent to that produced by 14 large electric power plants or $7.2 billion each year.[2]

In data centers, lifecycle energy costs exceed those of purchasing the energy-using equipment. Recent case studies (several of which are described in this article) for new construction show that some owners have saved a third or more of the facility's energy costs through efficient design strategies without

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[1] Naughton, P. (2001). Energy savings turn into cash-flow savings. *Semiconductor Fab Tech* (December). See http://www.fabtech.org/index.php?option=com_docman&task=doc_download&gid=153.

[2] Koomey, J. (2007). Estimating total power consumption by servers in the USA and the world. http://hightech.lbl.gov/documents/DATA_CENTERS/svrpwrusecompletefinal.pdf.

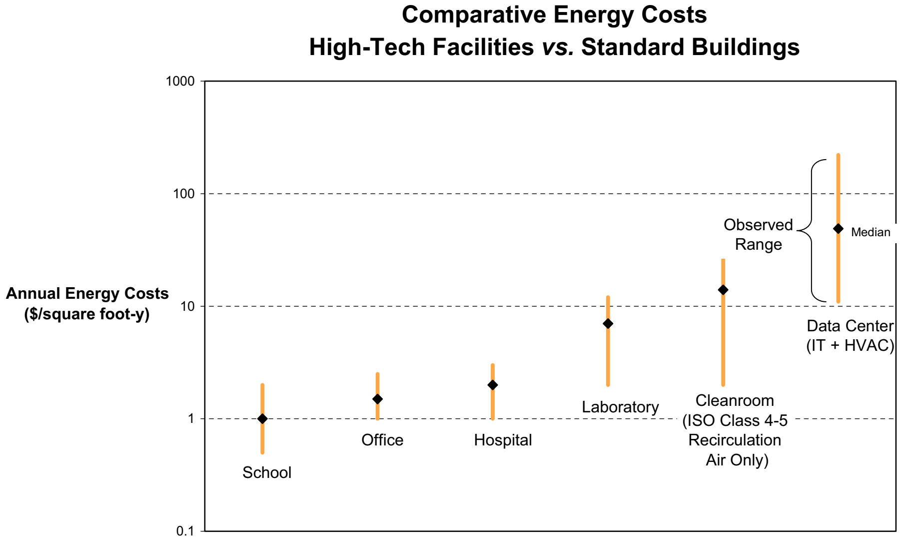

Fig. 1 Data on schools, offices, and hospitals from USDOE/EIA Commercial Buildings Energy Consumption Survey (1999 values). High-tech buildings from LBNL benchmarking databases (http://hightech.lbl.gov). Cleanrooms with the highest cleanliness standards can use significantly more energy than those shown

increasing project capital costs. Integrating energy efficiency throughout the design process has also yielded significant first-cost savings.

A case in point is The Molecular Foundry, a high-tech facility containing laboratory spaces, cleanrooms, and a small data center.[3] Through a combination of energy efficiency and green-power purchases, this facility achieved 35% reduction in energy use compared to that dictated by the prevailing energy performance standards and an 85% reduction in greenhouse-gas emissions at a lower initial cost than conventional practice (Fig. 2).

Capital- and operating-cost impacts must, thus, be considered in tandem to realize maximum value from facility improvements. In one of many real-world examples, thanks to improved heating, air-conditioning, and ventilation-efficiency upgrades, a major data center expanded computing power by 55% while keeping total facility energy use unchanged.[4]

Historically, the business cases for the development of cleanrooms and other specialized high-tech facilities typically focus on the capital–cost implications of revenue-producing equipment. The potential for simultaneously decreasing operating expenses such as energy consumption and building-related capital costs is inadequately characterized, and the impact on the bottom line not well analyzed. In the case of power consumption, the fluctuation in price and other constraints are often unanticipated – particularly, during periods of peak electrical demand. In some cases, risks and liabilities associated with power failure are clearly overestimated, resulting in the over-design of backup power systems. Also, risk-averse choices in the backup power technologies with strict emphasis on proven reliable technologies often result in missed opportunities. Meanwhile, inadequacies in the local utility distribution grid can pose a constraint to the construction or expansion of data centers.

The pursuit of energy efficiency is indeed a competitive issue. The operating costs to deliver products and services have been a key to driving margins and influencing stock prices in high-tech corporations. With rising energy prices and increased power outages, in-house energy reliability improvements and energy management have assumed increased strategic importance for upper management. Also important, a growing body of data shows that efficiency is associated with a healthier and higher quality work environment, especially regarding the use of outside make-up air.[5,6] On a

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[3] See http://hightech.lbl.gov/labs-mf.html.

[4] Blazek, M., Chong, H., Loh, W., & Koomey, J. G. (2004). Datacenters revisited: Assessment of the energy impact of retrofits and technology trends in a high-density computing facility. *Journal of Infrastructure Systems, 10*(3), 98.

[5] Placet, M., Winiarski, D., Heerwagen, J., Shankle, S., McMordie-Stoughton, K., Fowler, K., et al. (2003). The business case for sustainable design in federal facilities. US Department of Energy, Federal Energy Management Program. http://eetd.lbl.gov/emills/PUBS/Sustainable_Federal_Bldgs.html.

[6] Kats, G., Berman, A., Perlman, J., Alevantis, L., & Mills, E. (2003). The costs and financial benefits of green buildings: A report to California's sustainable building task force. Washington, DC: Capital E, http://eetd.lbl.gov/emills/PUBS/Green_Buildings.html.

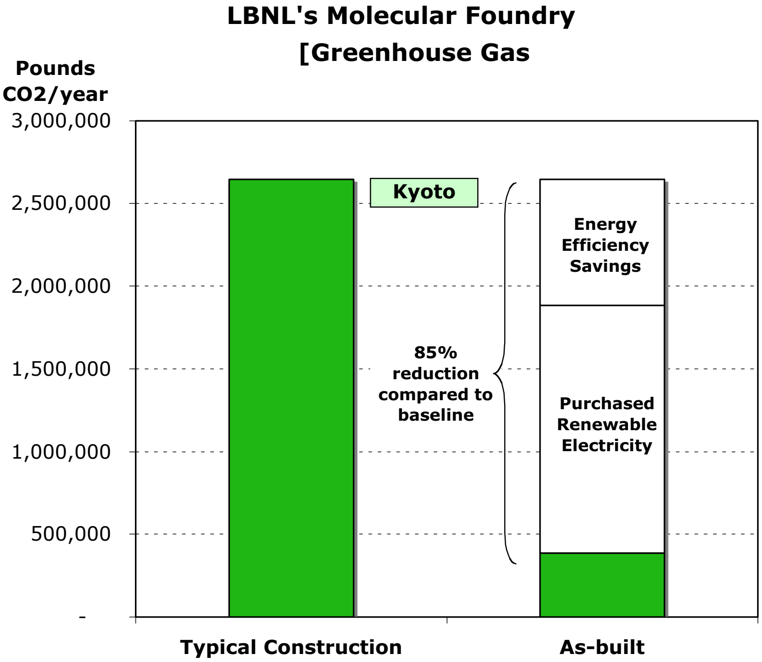

Fig. 2 Case study of the molecular foundry. Completed in 2006, LBNL's Molecular Foundry is a state-of-the-art six-story, 94,500 ft^2, $67 million user facility for nanoscale materials (plus $18 million in equipment), dedicated to supporting research in nanoscience by researchers from institutions around the world. Users from academia, government, and industrial laboratories with funded projects may write proposals requesting free access to the state-of-the-art instruments or techniques housed in the Foundry or to the highly skilled staff. From an energy- and water-management standpoint, this is a remarkable project in that it embodies best practices in the three major "high-tech" facility types, specifically wet and dry laboratories, a cleanroom, and a data center. Each of these spaces is highly resource-intensive and poses greater sustainability challenges than ordinary spaces. It is rare to find all three facility types under one roof. The facility has among the lowest electricity intensities of 56 projects currently included in the Labs21 benchmarking database and is responsible for 85% fewer greenhouse-gas emissions than a conventional facility meeting the ASHRAE 90.1 energy standards. Thanks to right-sizing of the mechanical systems, all of this was achieved at a reduced construction cost compared to typical practice. The project is winner of a 2006 Federal Energy Showcase Award, which recognizes buildings that take a comprehensive approach to energy management and stand out as exceptional models of energy efficiency, innovation, and sustainable design, and a US Green Building Council "Leadership in Energy and Environmental Design" (LEED) Gold certification

life-cycle basis, the energy consumption of high-tech systems can be the most significant source of environmental impacts.[7] For these reasons, energy efficiency is the keystone for the burgeoning sustainable/green-buildings movement and broader trends toward corporate responsibility and leadership.

Voluntary and mandatory programs (ranging from labeling strategies to building standards) are also driving the process. The Energy Star and LEED (Leadership in Energy and Environmental Design) labeling initiatives are the most well-known recognition programs. A complementary initiative – The Laboratories for the 21st Century Program ("Labs21") – defines best practices for laboratory-type facilities.[8] The primary guiding principle of Labs21 is that improving the energy efficiency and environmental performance of a laboratory requires examining the entire facility from a "whole building" perspective. Adopting this perspective allows laboratory owners to improve the efficiency of the entire facility rather than focusing on specific laboratory components. Improving the efficiency of individual components without examining their relation to the entire system can eliminate opportunities to make other more significant efficiency improvements.

More recently, the US Environmental Protection Agency was required to inform Congress on the current

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[7] Blazek, M., Rhodes, S., Kommomen, F., & Weidman, E. (1999). Tale of two cities: Environmental life cycle assessment for telecommunications systems: Stockholm, Sweden and Sacramento, CA. *Proceedings of the International Symposium on Electronics and Environment*, IEEE, May 11–13, 1999.

[8] See http://www.labs21century.gov.

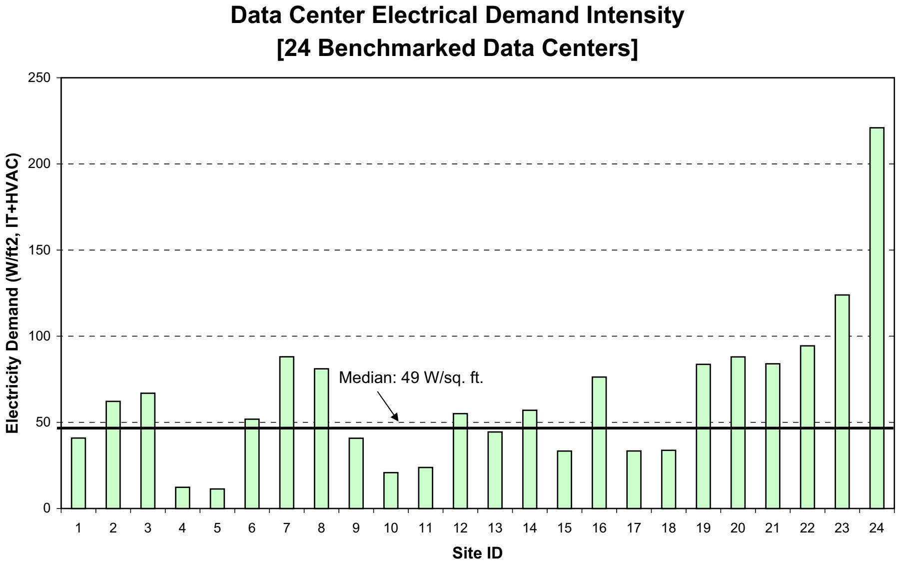

Fig. 3 *Bars* show total power requirement per unit floor area

state of efficiency in servers and data centers, as well as to address the efficiency improvement opportunity. In parallel, information-technology manufacturers formed an alliance to address efficiency and sustainability issues – The Green Grid.[9] This newly formed group plans to explore energy efficiency opportunities in servers and data centers, including development of standards, measurement methods, and new processes and technologies. The Department of Energy's Office of Industrial Technologies has also initiated a data center initiative under the "Save Energy Now" program. This initiative will develop assessment protocols and tools while providing leadership in obtaining benchmark data and disseminating best practices. The government will lead by example by evaluating Federal data centers and developing procurement specifications to advance energy efficiency. Other efforts are also underway – a consortium or electric utilities led by Pacific Gas and Electric was formed to coordinate on energy efficiency incentive programs. States (e.g., California and New York) are also leading efforts to efficiency measures, demonstrate innovative technologies, and disseminate best practices.

Many high-tech companies now include roadmaps for improvements in their energy efficiency as part of their ISO 14001 Environmental Management Systems. These forward-looking companies have realized benefits for themselves while fulfilling broader corporate citizenship goals.

Industries of the future lean heavily on energy-inefficient practices of the past

The high-technology sector is often where innovation first occurs – its facilities are sometimes referred to as the "racecars" of the buildings sector because new technologies and strategies to increase performance often trickle down to other building types. Yet, many of these facilities lag behind typical buildings in terms of attention paid to energy efficiency. Changing design practices can be challenging. The extreme criticality and high capital costs involved require confidence in the facility procurement process, from design to retrofit. The "racecar" analogy must not result in increased risks of system failures: Appropriate design practices must include risk analysis and appropriate redundancy for reliability enhancements.

Applying entrenched design practices within a dynamic marketplace with rising utility costs will not maximize life-cycle value. In many cases, older buildings are often retrofitted for high-tech uses without evaluating actual functional needs (e.g., ventilation and lighting) and resulting differences in power requirements. Emerging technologies[10] and thoughtful design and operation can yield very substantial reductions in energy operating costs.

This is the conclusion of a growing body of energy benchmarking.[11] For data centers, we have seen a

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[9] See http://www.thegreengrid.org/home.

[10] Mills, E., & Livingston, J. (2005). Traversing the valley of death. *Forbes*. November 18. See http://www.forbes.com/2005/11/17/utilities-emerging-tech-cz_1117energy_programs.html.

[11] See http://hightech.lbl.gov/benchmarking.html.

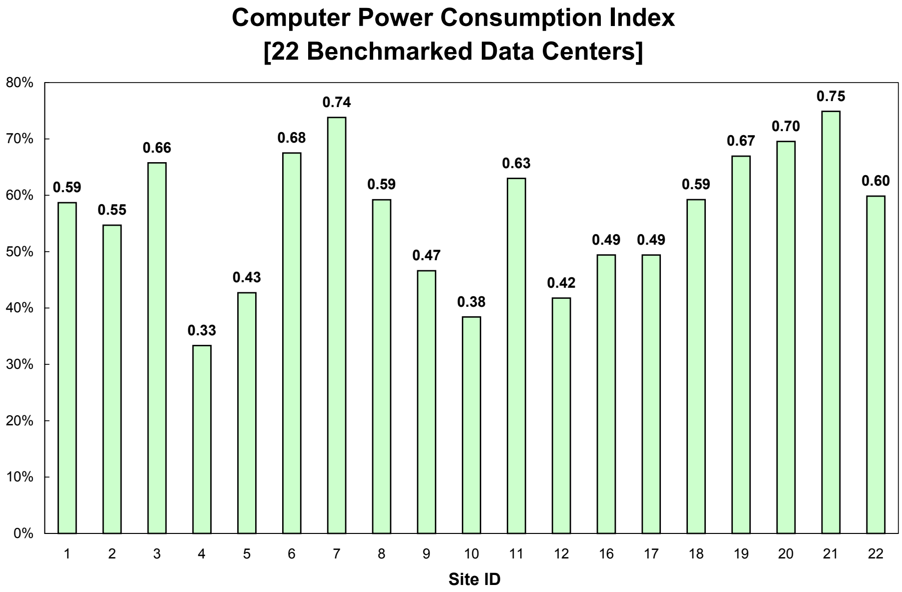

Fig. 4 Heating, ventilating, and air-conditioning costs can vary from about 33 to 75% of the total energy costs in data centers, a sign of hidden inefficiencies

factor of 20:1 variation in power requirements per unit floor area (Fig. 3) and a 2.5:1 variation in the effectiveness of the heating, ventilating, and air-conditioning (HVAC) system (Fig. 4). Efficiency indicators for labs and cleanrooms vary by 7:1 and 10:1, respectively (Figs. 5, 6). In the latter case, the implicit savings potential for a single mid-sized cleanroom is $350,000 per year. The most efficient of these buildings do not represent the full potential; best practices would result in even higher performance.[12]

Opportunities abound for individual pieces of equipment, sub-systems, or entire facilities. Among a myriad of examples:

- We have noted a fivefold variation in the efficiency of cleanroom fan-filter units on the market today.[13]
- We have observed a sevenfold variability in the part-load efficiency of cleanroom chillers. It is telling that a chiller in a cleanroom can use $300,000 in energy each year (equal to its first cost!), and yet, they are typically not monitored or optimized.
- Avoidable energy costs often stem from sub-optimal facility operation. Simultaneous heating and cooling and/or humidification and dehumidification, for example, are strikingly common problems often corrected through commissioning efforts.

These examples focus on the building envelope and environmental-control infrastructure. The processes within the buildings can also be made more efficient. For example, analyses show that improving mediocre server power supply efficiencies of 70% toward 95% yields a net present value in energy savings that will exceed the equipment's purchase price. This translates into an energy savings potential of up to $1.5 million/year for one data center evaluated (Fig. 7).

The key to energy-efficient design – systems analysis

The challenge and opportunity of energy efficiency extends beyond swapping in and out individual components. Most of the gold to be mined is found at what can be thought of as the "systems level." Individual efficient

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[12] See Tschudi, W., Rumsey, P., Mills, E., & Greenberg, S. (2005). Measuring and managing energy use in datacenters. *HPAC Engineering* (in press), LBNL/PUB-945 see http://hightech.lbl.gov/Documents/CLEANROOMS/HPAC_CR_BestPrac.pdf and Tschudi, W., Mills, E., Rumsey, P., & Xu, T. (2005). Measuring and managing energy use in cleanrooms. *HPAC Engineering* (in press), LBNL/PUB-946, see http://hightech.lbl.gov/Documents/DATA_CENTERS/HPAC_DC_BestPrac.pdf.

[13] Jeng, M.-S., Xu, T., & Lan, C.-H. (2004). Toward green systems for cleanrooms: Energy efficient fan filter units. *Proceedings of SEMI Technology Symposium: Innovations in Semiconductor Manufacturing*, SEMICON West 2004. San Francisco (July) pp 73–77. LBNL-55039. http://hightech.lbl.gov/Documents/LBNL55039_TXu.pdf.

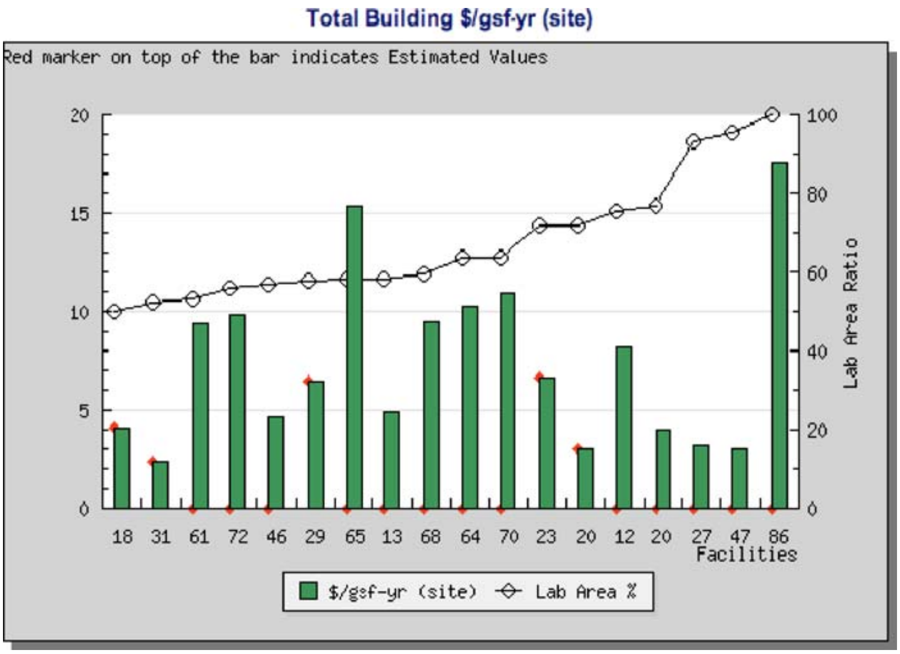

Fig. 5 Normalized annual energy costs in laboratories (facilities with >50% of total floor area in labs)

components (e.g., an efficient fan) often under-perform if not properly controlled and integrated with other components in the facility. Sometimes the opportunities are far from glamorous: e.g., duct and piping systems that have low-friction elbows or use high-quality filters can facilitate flow and, thereby, save chiller, fan, and pumping energy. In another example, simply rearranging server racks so that the hot exhaust of one server is not the inadvertent intake for another already overheated one. Flat panel displays use significantly less energy than their predecessors – CRTs – emit less heat, allow for downsizing of central chiller plants, and are preferred by most employees. Indeed, it is these factors, more than energy savings, that drove the transition from CRT to flat-screen technology. A new generation of emerging technologies offers further opportunities to capture component- and systems-level efficiency gains (Fig. 8).

Increasingly complex and powerful automation and control systems enable particularly effective system-level energy savings opportunities. Be it lights that are turned off when not needed or variable-speed fans that only need to run at full speed 3 h per month, better control can save enormous amounts of energy while ensuring that adequate building services are available when demanded. The non-energy benefits of controls are numerous; recently, it has been found that buildings with more advanced ventilation control systems can be more responsive and, thus, resistant to chemical and biological attacks.[14] Control strategies that maximize the use of outside air can also improve the overall air quality for the occupants in the building, which decreases heating or cooling energy requirements. The macro-level potential is significant. For example, IT equipment consumes about $8 billion/year of energy in the USA alone. A single high-powered rack of servers consumes enough energy in a single year to power a hybrid car across the USA 337 times.

Among the findings of a design charette held in 2003, an integrated systems-level strategy using currently available best practices could reduce data center energy use by two thirds.[15] One systems-level opportunity in data centers is to rethink the tradition of multiple power supplies and their AC–DC conversions, each of which introduces multiplicative inefficiencies and generates waste heat that must be removed with an additional energy penalty.[16] The irony is that many data centers are co-located with traditional telephone technologies that routinely use

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[14] See http://securebuildings.lbl.gov/.

[15] Rocky Mountain Institute (2003). Design recommendations for high-performance datacenters: Report of the integrated design charette.

[16] Stansberry, M. (2005). Power-saving technologies in the datacenter. *TechTarget Network* (November 10). See http://searchdatacenter.techtarget.com/originalContent/0,289142,sid80_gci1144396,00.html.

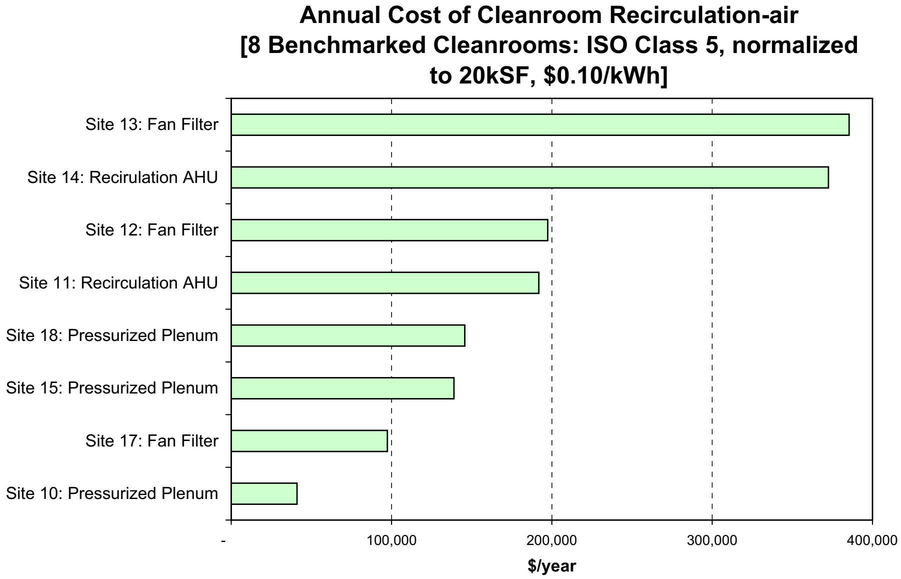

Fig. 6 Note that these estimates are for rooms with similar size and levels of contamination control (ISO class 5). The results exhibit a factor of nearly 20 in energy costs. Each *bar* corresponds to an individual cleanroom from the LBNL database, hypothetically normalized for size (to 20,000 ft^2) and energy prices ($0.10/kWh) for comparison purposes

DC power and, consequently, improve efficiency, increase backup power capacity, and filter signals to improve power quality. Most data center server racks are not currently powered this way, but with the advent of servers that can operate with either AC or DC, it is possible to use the DC powering approach, thus, eliminating extra power conversion steps and losses. Other benefits include reduced cooling needs, higher equipment densities, and reduced heat-related failures. Under typical practice, power supplies convert high-voltage AC power into the low-voltage DC power needed by the circuitry found within servers, routers, hubs, switches, data storage units, and other electronic equipment. These conversions entail losses, even for the most efficient power supplies. In a demonstration project hosted by Sun Microsystems and contributed to by about two dozens of equipment vendors and service providers, facility-wide energy-efficiency improvements of 28% were achieved compared to typical technologies currently in use (61 versus 85% system efficiencies) and 5–7% compared to the best available technologies[17] by replacing the chain of AC power generation, AC–DC–AC uninterruptible power supplies, and AC–DC power supplies with a direct DC power system in data centers.

Some strategies must be implemented by component manufacturers rather than by on-site facility engineers. For example, the great majority of servers are operated at very low percentages of their computing capacity the great majority of the time. However, power consumption in today's servers varies only slightly, as the computing use ranges from idle to completely busy. This is akin to a car using the same amount of gasoline idling at a stop sign as when maximally accelerating. Some new servers reduce their power consumption (to a limited degree) as the amount of needed computing drops. The energy savings from this technique are large. Facility operators can, thus, save energy by specifying premium efficiency for new equipment purchases.[18] In addition to direct energy savings, efficient computers and servers produce less waste heat, thus, yielding cooling energy savings within the HVAC system.

Moving beyond hardware "fixes," further energy savings can be obtained by improving data management and IT processes. The fundamental strategy for improving computational productivity on underutilized equipment, "consolidation," simply entails running more applications on fewer servers. This is common sense but is rarely implemented in an optimal fashion. A more refined form of consolidation is "virtualization," wherein each application has its own copy of the operating system so that, if one application crashes, the server itself and other applications are not impacted. In both cases, fewer redundant servers are needed to maintain the same standard of reliability. Institutional server users

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[17] Ton, M., Fortenbery, B., & Tschudi, W. (2007). DC power for improved data center efficiency. Lawrence Berkeley National Laboratory Report, http://hightech.lbl.gov/documents/DATA_CENTERS/DCDemoFinalReportJan17–07.pdf.

[18] For example, see the 80 PLUS program (http://www.80plus.org/) for desktop computers and servers with efficient power supplies.

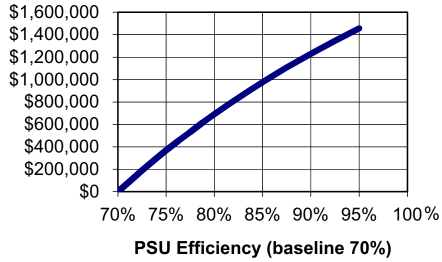

Fig. 7 Savings potential in a typical data center using energy-efficient server power supply units (PSUs). Based on an electricity price of $0.10/kWh

report 5–10% utilization factors, indicating that the overall technical potential for consolidation could be well over 50% savings. Mainframe computers have always been configured in this fashion, but the practice is rarely used for small servers. Pacific Gas and Electric Company claims to be the first energy utility to offer customer rebates for virtualization, with awards ranging as high as $4 million per facility, which can translate into annual energy cost savings of $600–1,200 per server removed.[19] Efforts are also being made on storage virtualization (better use of powered storage) and network virtualization (fewer physical powered network connections from a given server).

In a case study exemplifying the preceding “systems integration” philosophy, a major biotech firm recently designed a new five-story facility. The building emphasizes natural lighting and materials, including a shaded top-floor deck and promenade on each floor’s southern exposure. These measures, plus high-performance glazing, flat screen computers, low-pressure-drop HVAC design, and efficient right-sized lighting systems resulted in a 20% reduction of the mechanical heating and cooling system size, with corresponding capital–cost savings (a process we call “right-sizing”). The facility used three air-conditioning units for two perimeter zones and one interior, and the resultant duct sizing allowed the overall building height to be lowered by 2.5 feet for significant construction cost savings. The reduced building volume and subsequent reduction of perimeter exposure to environmental heat loads led to additional HVAC peak capacity reductions. The cumulative HVAC capacity savings also reduced the sizing of the back-up generator, resulting in additional first-costs savings. These construction cost savings exceeded the added first costs of improved glazing to save the project approximately 1% of total construction costs (worth approximately $400,000). The building continues to perform about 18% better than the efficiency levels mandated by the California energy efficiency standards (some of the most stringent in the country), saving $17,000 each year in heating, ventilation, and air-conditioning costs). The project also garnered for a rebate from the local utility, further defraying costs. The facility provides a good indoor environment for workers, who also appreciate working in a building that incorporates environmentally appropriate design. The resultant system-sizing benchmarks set the standard for similar cost savings and efficiency improvements through replication in future projects. As its profits are driven by the creativity of its employees, personal productivity improvements may ultimately be the greatest benefit of this integrated design effort. Buildings designed to reduce environmental impact can be better places to work, which translates into better morale, lower absenteeism, and reduced turnover.

“Rules of thumb” can be “all thumbs”

One of the ways in which inefficiency becomes institutionalized in both design and operation is the unquestioning perpetuation of certain “rules of thumb.” For example, decades ago, through an unscientific process, it was deemed that air should flow into laboratory fume hoods (and other containment devices such as gas cabinets) at no less than 100 ft per min (the so-called face velocity). This is one of the reasons that a single fume hood uses nearly four times as much energy as a typical home.[20] Field measurements, however, have shown that slower speeds can maintain or even improve safety (by reducing the risk of undesirable turbulence in the hood opening), and, of course, save large amounts of energy in the process.[21]

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[19] See http://www.pge.com/news/news_releases/q4_2006/061108.html.

[20] Mills, E., & Sartor, D. (2004). Energy use and savings potential for laboratory fume hoods. *Energy*, *30*, 1859–1864. LBNL-55400. http://eetd.lbl.gov/emills/PUBS/Fume_Hood_Energy.html.

[21] Bell, G., Sartor, D., & Mills, E. (2001). Development and commercialization of a high-performance laboratory fume hood. LBNL-48983 (rev.) http://eetd.lbl.gov/emills/PUBS/BerkeleyHood.html.

Fig. 8 What is in the R&D pipeline?

The energy consumed by high-tech industries and institutions represents an attractive and often untapped opportunity for energy savings. R&D projects sponsored by the U.S. Department Of Energy, U.S. Environmental Protection Agency, New York State Energy Research and Development Authority, the California Energy Commission's Public Interest Energy Research Program, and others have included benchmarking energy performance and the development of technologies, tools and strategies for addressing various aspects of the overall efficiency opportunity for this market. Much has been accomplished, yet further development will enable these buildings to fully reach their energy savings potential. While improving each piece of the efficiency puzzle provides important gains, new technologies in the R&D pipeline have the potential for 30 to 50% further improvement beyond current best practices. Examples include:

- The primary energy service provided in cleanrooms is the control of particles in the space. The question of whether higher levels of ventilation necessarily yield higher levels of particle control has not been adequately addressed. New technologies will exploit the potential for dynamically adjusting ventilation rates in response to real-time particle-count measurements. With demand-controlled filtration, desired environmental conditions can be maintained without excessive energy use. The results of a recent field study were very positive, indicating an economic payback time of 1 to 4 years, depending on whether or not the facility's ventilation system is already equipped with a variable speed drive.

- Fan filter units (FFUs) are increasingly used in contamination-control environments such as cleanrooms. They consist of a small fan, controller, and a filter enclosed in a box, to maintain specific airflow. However, there is no standard procedure of measuring FFU performance or energy use, which presents an obstacle for users wanting to specify or purchase efficient models. A new standardized method will soon be available, and has shown that efficiencies of products now on the market vary by a factor of three.

- Typical server power supplies operate at roughly 65 to 75% efficiency, meaning that 25 to 35% of all the energy consumed by servers is wasted (converted to heat) within their power supplies. The technology exists to achieve efficiencies of 80 to 90% in conventional server power supplies.

- One barrier to the use of a proven technology (outside-air economizers, which bring in large amounts of outside air to cool internal loads when weather conditions are favorable into a new context (data centers) is the perception that introduction of pollutants and loss of humidity control in the space will disrupt the process. New data from eight data centers Northern California has shown that outside air can in fact be used, and achieve energy savings while keeping particle counts and humidity within levels prescribed by existing standards. Cooling energy savings were evaluated at one site, and were found to be on the order of 5%, which may be increased with optimization.

- Backup power systems are essential for mission-critical facilities, yet while in standby mode their energy use can be unnecessarily high. Efficiency losses in uninterruptible power supplies (UPSs) represent about 5 to 12% of the energy consumed in data centers. In fact, the typical backup system will use more energy while in its standby mode than it will ever generate for the facility it serves. Manufacturer specifications can differ widely from measured results because of differences in loading conditions and test procedures. New cost-of-ownership tools will enable facility owners to make better technology purchasing decisions.

- A new generation of high-performance laboratory fume hoods promises to cut costs in half (see Figure 10).

There are similar forms of "conventional wisdom" regarding cleanroom air recirculation rates. The purpose of cleanroom air movement is to control contaminants and minimize product defects. Boosting the airflow, however, is not the best way to do this, as it increases turbulence-induced contamination risks while consuming significantly more energy. Benchmarking studies have shown that some cleanrooms provide over six times the air-change rates of others within the same cleanliness classification, resulting in significant capital and operating cost impacts (Fig. 9). As a way to further optimize airflow, an emerging strategy – demand-controlled filtration – uses direct measurements of contaminants to determine air circulation rates. Case studies have demonstrated 60 to 80% energy savings during periods when airflow is reduced in this fashion. An annual savings potential of $138,000 was estimated to be obtainable simply by lowering air circulation rates when the cleanrooms are not occupied – an essentially no-cost measure.[22] In

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[22] Tschudi, W. T., Faulkner, D., & Hebert, A. (2005). Energy efficiency strategies for cleanrooms without compromising environmental conditions. *ASHRAE Transactions*, *111*(pt. 2, paper no. DE-05–9–1), 637–645.

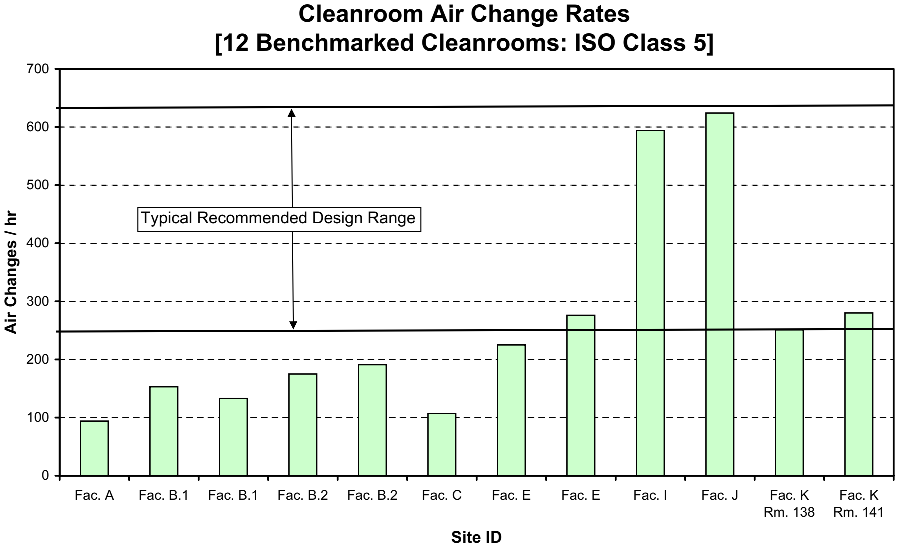

Fig. 9 The chart tells us two important things: Firstly, there is more than a factor-of-six variation in air-change rates for cleanrooms of an identical cleanroom "class" (cleanliness level), and, secondly, that many cleanrooms certified as sufficiently clean for their designated function operate at well below the air change rates called for by rules of thumb

such cases, raising energy efficiency and improving process control go hand in hand.

The systematic over-sizing of utility systems and, consequently, oversized cooling equipment is a pervasive problem that typically results from over-estimating electrical demands, thereby, creating fictitious sources of heat within a facility. Over-sizing is often aggravated by outdated rules of thumb about power density combined with overestimates of future growth in facility output. This is compounded by the aggregate impact of inadvertent redundant over-sizing by multiple parties to the design and construction process (owners, process engineers, electrical engineers, HVAC engineers, etc.), each adding "safety factors" to their sizing calculations, often unaware that others in the decision chain have already done so. The result is not only systems that have much higher first cost than they should but also higher operating costs because of excessive and inefficient on–off cycling and/or part-load operation.

Erroneous rules of thumb can also lead to obstacles in citing facilities and gaining utility service. Conventional wisdom has been that data centers can require an electrical grid connection to support 250 (or more) watts per square foot of space. Our benchmarking results of 24 conventional data centers found an average value of 49 W in practice and a maximum value of about <100 in most cases W (Fig. 3). A larger survey by the Uptime Institute came to nearly identical results.

Quality assurance includes energy efficiency

Quality assurance (e.g., design intent documentation, commissioning, and diagnostics) is essential to ensuring that new projects go smoothly and to maintaining energy performance after facility start-up.[23] As buildings become more complex, the need for quality assurance only increases. In one example, an efficient chiller was installed in a cleanroom, and, shortly after installation, an additional 50% energy savings was achieved by (properly) resetting the variable speed controls. At another site, quality assurance studies found that a $1,000,000 chiller called for in a plant expansion was entirely unnecessary.

A recent analysis of efforts to identify and remedy energy-related performance problems (a process known as "commissioning") found about 20%

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[23] Hydeman, M., Seidel, R., & Shalley, C. (2005). Staying on-line: Datacenter commissioning. *ASHRAE Journal*, pp. 60–65, April. See http://hightech.lbl.gov/DCTraining/docs/wsjon-data-ctr-power.pdf.

whole-building energy savings ($3.60 per square foot annual savings, averaged across a group of high-tech buildings) were achieved with a 5-month payback time.[24] These results were significantly better than observed in other building types, such as office buildings. Additional non-energy benefits included early identification of maintenance problems, safety issues, avoiding premature equipment failure, etc. In addition to verifying proper system operation and fulfilling user requirements, commissioning ensures that problems get fixed during warranty and the additional first-cost savings can be achieved by reducing callbacks or avoiding construction-defects litigation. In mission-critical facilities, commissioning demonstrates the ability of the building to perform at the extremes of its design intent and pinpoints problems that could later result in costly downtime. When performed during design and construction, first-cost savings typically more than pay for the cost of commissioning; the energy savings are icing on the cake.

Energy efficiency is the tip of the iceberg

High-energy-performance facilities also tend to accrue considerable non-energy benefits, such as superior safety, risk management, improved process control, and maximized up-time. These are rarely included in lifecycle cost analyses and associated decision-making. Some examples follow:

- *Improved productivity:* Many laboratories have a need to add fume-hood workstations but lack adequate air supply or exhaust capacity. Emerging high-performance hoods (with lower face velocities that maintain or improve safety) will allow the replacement of one conventional hood with two new hoods (Fig. 10) without starving the lab for air.[25] This will avoid significant lab downtime and high cash outlays for increasing mechanical heating and cooling capacity (often so expensive that it is not done). The benefits in terms of greater productivity or output will dwarf the (still significant) energy costs savings of several thousand dollars per hood per year.

  Excessive heat – a direct outcome of energy inefficiency – has become a limiting factor in the number of servers (productivity) that data centers can house.[26] Efficient power supplies can yield about $3,000/year per rack in energy savings and allow about 20% more servers per rack.[27]
- *Improved process control:* Mini-environments improve environmental control in cleanrooms and are only now being assessed for their value in reducing energy costs (Fig. 11).[28] Driven by quality control benefits (smaller space without human occupancy), energy savings can also result from no longer needing to eliminate all particles from enormous surrounding "ballroom" areas. The use of mini-environments in the latest wafer fabs and the benefits associated with focused environmental control has resulted in significant reductions in air recirculation rates, with common decreases on the order of 35%.
- *Enhanced reliability:* Many energy efficiency measures improve reliability. For example, when using outside air for cooling (also known as "free cooling"), the mechanical compressor effectively

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[24] Mills, E., Friedman, H., Powell, T., Bourassa, N., Claridge, D., Haasl, T., & Piette, M. A. (2004). The cost-effectiveness of commercial-buildings commissioning: A meta-analysis of energy and non-energy impacts in existing buildings and new construction in the united states. Lawrence Berkeley National Laboratory Report No.56637 http://cx.lbl.gov.

[25] Bell, G., Sartor, D., & Mills, E. (2001). *op cit.*

[26] Clark, D. (2005). Power-hungry computers put datacenters in bind - newer hardware guzzles electricity and spews heat, requiring costly alterations. *Wall Street Journal*, p. A1 (14 November). See http://hightech.lbl.gov/DCTraining/Documents/WSJondatacenterpower051114.pdf.

[27] Calwell, C., & Griffith, B. (2005). Enabling high efficiency power supplies for servers: Update on industry, government and utility initiatives. Presented at the *Intel Developer Forum*. Cited benefits correspond to a change from 70 to 83% efficiency. See http://hightech.lbl.gov/Presentations/PTMS009-IDF-2005-final.ppt.

[28] Xu, T. (2005). Investigating the performance of a minienvironment system. Presentation at Contamination Control Technical Session, The 51st ESTECH Conference May 1–4, 2005, Hyatt Regency Woodfield, Schaumburg, Illinois, The Institute of Environmental Sciences and Technology (IEST). http://hightech.lbl.gov/Presentations/Minienv_ESTECH2005.ppt Technical paper published in the *Proceedings of The 51st ESTECH Conference.*

Fig. 10 Prototype high-performance fume hood. Air is introduced in the frame (face) of the hood, in front of the worker (see grill under right wrist), maintaining or improving containment and reducing energy use. Typical designs draw air from the general lab space around the worker, causing turbulence and higher-than-necessary fan energy use. Smoke in right panel shows air entering through the frame

becomes a backup system that can be used to augment or replace the primary system when needed. Water-side free cooling achieves this same goal. Reduced chiller operating hours extends their service life, increasing the likelihood that they will be available as a redundant cooling source in times of need. Operating fans and motors in lower-pressure-drop systems not only requires less energy but put less stress on the devices, thereby, reducing the risk of failure and extending service life. Eliminating some power conversions by directly distributing DC power is another example. As discussed above, it has been demonstrated that some of these conversion devices can be eliminated, thereby, reducing the number of components in the power distribution path. This results in fewer potential points of failure in the system and improved reliability.

In data centers, some analysts have observed that proximity of fans to computer drives increases the numbers of rewrites/retries (eroding productivity). Alternative cooling strategies now in the R&D phase may eliminate these fans altogether. Another benefit of doing so is to reduce the problem of fan noise in server farms.

Backup power systems are often essential, yet rarely optimized. In some cases, their implementation is limited because of hesitance to try new technologies (e.g., flywheels or fuel cells) or dictated by customer requirements (some web-hosting facilities have dedicated diesel generators for customers). While not a panacea, energy-storage flywheels promise to be efficient and compact than standard uninterruptible power supplies (UPS), thereby, reducing floor-space-requirement-associated construction costs, and they can be 20% more efficient than battery back-up systems.

- *Reduced operation and maintenance costs:* Full-throttle operation is often designed into a project, although it is not needed. As one of the many examples, applying variable-speed controls to traditionally constant volume air- or fluid-movement applications can enhance performance and increase system flexibility while saving energy. The added benefits of reducing operational challenges, extending equipment life, increasing diagnostic capabilities, and minimizing downtime during modifications often eclipse the energy savings benefits.

Extended-area filters in cleanroom ventilation systems save energy (by reducing friction losses known as “pressure drop”) but also reduce maintenance shutdowns – as they need to be replaced half as often – and reduce filter purchase and waste disposal costs. When integrated properly, lower system pressure drops lead to less ventilation horsepower requirements and overall project first-cost savings.

Fig. 11 Cleanroom mini-environment

Greening the bottom line

While the productivity benefits cited in this paper can be difficult to quantify, energy savings alone can materially reduce total costs of ownership. Most of the lifetime costs for high-tech equipment are borne during the operations portion of the product/service lifecycle rather than during the manufacturing and shipping phases that are associated with the initial capital purchase prices of such technology.[29] Many efficiency improvements yield an annualized return on investment of 50 to 100%.

Recent retrofits of 36 data centers yielded an aggregate energy savings of $2 million/year with an average payback time of less than 3 months (Fig. 12). Motorola has similarly observed payback times of even less than 1 month – achievable without capital investment (labor only) – and overall savings of $5 million per year across a portfolio of projects – translating into real reductions in wafer costs.[30]

As noted above, quality assurance measures such as commissioning can yield large cost-effective savings. In new construction, there can be immediate positive cash flow, thanks to first-cost savings achieved by using a systems approach and right-sizing. Benefits can, thus, accrue to both operating and capital budgets.

Energy efficiency also makes sense in terms of financial asset management, as property values are a function of net operating income (the difference between gross income and expenses).[31] As a major expense item, any reduction in energy costs translates into increased value of the real estate asset. Valuations vary depending on markets and market conditions, but capitalization (CAP) rates of 5 to 10% are common. As property value equals net operating income (gross income − pretax expenses) divided by the CAP rate, a dollar of energy savings translates into $10 to 20 in increased property value. An additional dimension is the hedging benefit to an operation that is less vulnerable to energy price shocks, i.e., lower overall energy use translates into a smaller shock to bottom-line operating expenses in the event of abrupt price increases. Additional (non-energy) economic benefits, such as improved working conditions, can be captured by pursuing a broader "green buildings" design strategy.[32]

However, energy efficiency improvements must compete with other capital investments that often yield payback times of less than 1 year, a much higher hurdle than faced by energy efficiency in other sectors. As a case in point, a recent data center retrofit proposal that would have yielded $264,000/year in energy savings with a 2.7-year payback time was rejected as uncompetitive with other uses of capital.

Where there is a will, there is an (efficient) way: toward best practices

It is often asked: "If energy efficiency is so profitable, then why is it not already being done"? In an ideal

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[29] Blazek, M, Rhodes, S., Kommomen, F., & Weidman, E. (1999). Tale of two cities: Environmental life cycle assessment for Telecommunications Systems: Stockholm, Sweden and Sacramento, CA. *Proceedings of the International Symposium on Electronics and Environment*, IEEE, May 11–13.

[30] Naughton (2001), *op cit.*

[31] Mills, E. (2004). Amplifying real estate value through energy & water management: From ESCO to 'energy services partner.' *Proceedings of the 2004 ACEEE Summer Study on Energy Efficiency in Buildings*, Asilomar, CA August 22–27. LBNL-52768. http://eetd.lbl.gov/emills/PUBS/EnergyServicesPartners.html.

[32] U.S. Green Buildings Council. N/D. "Making The Business Case for High Performance Green Buildings." USGBC, Washington, DC, 12 pp. See http://www.wgba.org/artman/uploads/making_the_business_case-cd.pdf.

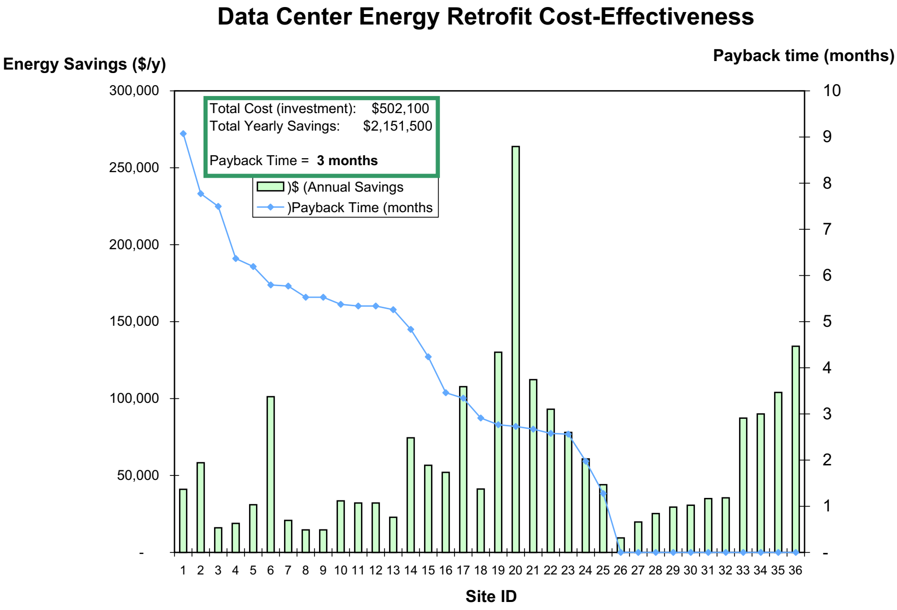

Fig. 12 Actual results for energy-efficiency upgrades at 36 data centers. Zero-cost items were labor only, using in-house salaried staff

world, it would be. But, in practice there are barriers. Cross-cutting barriers include generic resistance to change and that the "mission-critical" nature of the processes in high-tech industries has been misconstrued as a reason to pass over programs that address energy efficiency. Specific barriers include the separation between capital and operating budgets, differences in incentives for owners and tenants, lack of trained staff, fragmentation among the many trades that must interact to create and maintain facilities, "value engineering" processes in new construction that result in hasty cuts to valuable efficiency design features to offset unrelated cost overruns, and other perceived risks that may not be in fact material. If improperly applied, efficiency strategies could have adverse impacts on uptime; yet, the opposite has also shown to be true if good design practices are followed. Time to market is another key factor: Energy efficiency upgrades can be seen as undesirable if they prolong facility construction or renovation time.

If all of these barriers are swept aside, accounting disincentives may remain, e.g., wherein lagged historically based internal utility recharges effectively dilute the savings attributed to a specific production unit that may have implemented an otherwise effective savings program. As counterintuitive as it may seem, these barriers can cause the most innovative industries to be the most reluctant to try new ideas when it comes to energy management.

The reasons for the lack of attention to this issue are numerous, but there are two drivers that have resulted in systematic inefficiencies: inadequate backup power configurations and overestimates of backup power requirements.

Below, we provide a generalized framework for institutionalizing best practices. Excellent resources are available to help formulate a corporate strategy.

- Institute an energy management program, integrated with other functions (risk management, cost control, quality assurance, employee recognition, training).
- Integrate life-cycle cost analysis as a decision-making tool, including energy price volatility and non-energy benefits (e.g., reliability and environmental impacts).
- Adopt quantifiable voluntary goals based on best practices.
- Create design intent documents[33] to include all key stakeholders, reduce risks of client dissatisfaction, and keep the team on the same page while clarifying and preserving the rationale for key design decisions.

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[33] Mills, E., Abell, D., Bell, G., Faludi, J., Greenberg, S., Hitchcock, R., Piette, M. A., Sartor, D., & Stum, K. (2002). Design intent tool: User guide. LBNL/PUB-3167. http://eetd.lbl.gov/emills/PUBS/Design_Intent_Tool.html.

- Minimize construction and operating costs by incorporating energy optimization standards and performance metrics at the earliest phases of the design; avoid excessive/redundant “safety margins” and right-size to trim first costs.
- Include integrated monitoring, measuring, and controls (building management system) in the facility design and operations and maintenance philosophy.
- Benchmark existing facilities, track performance, and periodically assess opportunities.
- Incorporate a comprehensive commissioning (quality assurance) process into new construction and renovation projects.
- Include periodic “re-commissioning” in the overall facility maintenance program.
- Evaluate the potential for energy-efficient on-site power generation, including combined heat and power technologies.
- Ensure that all facility operations staff are provided with site-specific training that includes identification and proper operation of energy-efficiency features.

At several levels, energy efficiency can be thought of as a form of risk management. Of course, it manages the risks and uncertainties of future energy price increases by reducing the amount of various energy commodities consumed. More importantly, the types of quality assurance described above mitigate performance risks, help ensure a safe, comfortable, and healthy indoor environment, and can prevent business interruptions by proactively detecting and remedying performance problems or increasing the ability for a facility to use on-site power in the event of disruptions of the power grid.

Enterprise-wide success requires a marriage of the bottom-up ingenuity and motivation among engineering staff with top-down vision and open candid two-way communication among all levels of the organization. The best practices offered in this article provide a starting point for closing this gap.

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