ENERGY EFFICIENCY IN CALIFORNIA LABORATORY-TYPE FACILITIES

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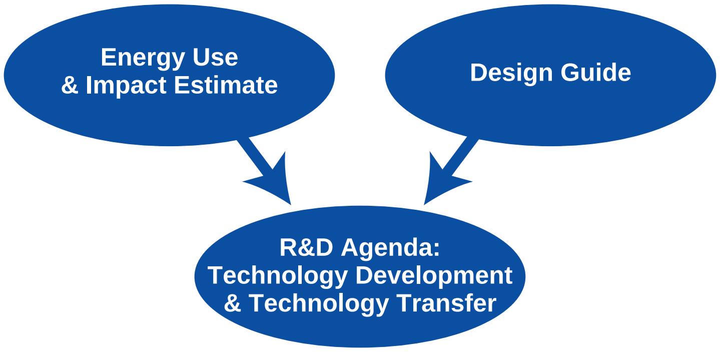
The central aim of this project is to provide knowledge and tools for increasing the energy efficiency and performance of new and existing laboratory-type facilities in California. We approach the task along three avenues (**Figure 1**): (1) identification of current energy use and savings potential, (2) development of *A Design Guide for Energy-Efficient Research Laboratories*, and (3) development of a research agenda for focused technology development and for improving our understanding of the market

Figure 1

Project Elements



Laboratory-type facilities use a considerable amount of energy resources. They are also important to the local and state economy, and energy costs are a factor in the overall competitiveness of industries utilizing laboratory-type facilities. Although the potential for energy savings is considerable, improving energy efficiency in laboratory-type facilities is no easy task, and there are many formidable barriers to improving energy efficiency in these specialized facilities. Insufficient motivation for individual stakeholders to invest in improving energy efficiency using existing technologies as well as conducting related R&D is indicative of the “public goods” nature of the opportunity to achieve energy savings in this sector.

Due to demanding environmental control requirements and specialized processes, laboratory-type facilities epitomize the important intersection between energy demand in the buildings sector and in the industrial sector. Moreover, given the high importance and value of the activities conducted in laboratory-type facilities, they represent one of the most powerful contexts in which energy efficiency improvements stand to yield abundant non-energy benefits if properly applied.

The main findings of this study are as follows:

Energy Use and Savings Potential

- Laboratory-type buildings represent 51 million square feet of floor area in California.

- Energy intensities are four- to five-times higher than those found in ordinary (non-laboratory) buildings, such as offices. In the case of cleanrooms, intensities are 10-100 times higher, depending on the cleanliness classification.

- In end-user categories representing Standard Industrial Codes (SIC) 2700-8734 (253 categories), laboratory-type energy use represents 35% of total energy (38% of total electricity and 27% of total natural gas). In the absence of energy-efficiency improvements, these shares are projected to grow to 40%, 43%, and 29%, respectively, by the year 2015. The most important segments are cleanrooms, healthcare, universities, and national laboratories.

- In the above-mentioned SIC user categories, primary laboratory energy use in California 1993 was 111 x 10^{12} BTUs (TBTU), including 8.8 billion kilowatt-hours of electricity (2100 megawatts) and 21 TBTUs of natural gas. In the absence of energy-efficiency improvements, projected growth is 131% (3.9%/year) to the year 2015.

- The corresponding energy cost in 1993 was $700 million annually, growing to $1,640 million by the year 2015.

- Based on our estimate of an overall savings potential of 50% in new and existing buildings, savings by the year 2015 (compared to a frozen-efficiency baseline) amount to 128 TBTUs, valued at $820 million/year, including 10.4 billion kilowatt-hours of electricity (2500 megawatts) and 21 TBTUs of natural gas.

Energy-Efficient Laboratory Design

- In this project, we identify a variety of barriers to energy-efficiency in laboratory-type facilities.

- We articulate an integrated design philosophy for optimizing energy-efficiency in laboratory-type facilities, and identify some key leading-edge technologies and strategies for capturing energy savings and overcoming barriers.

- We present a separate report entitled *A Design Guide for Energy Efficient Research Laboratories*. This document provides a detailed and holistic framework to assist designers and energy managers in identifying and applying advanced energy-efficiency features in laboratory-type environments. The Guide fills an important void in the general literature and compliments existing in-depth technical manuals. Considerable information is available pertaining to overall laboratory design issues, but no single document focuses comprehensively on energy issues in these highly specialized environments. Furthermore, practitioners may utilize antiquated rules of thumb, which often inadvertently cause energy inefficiency. The Guide helps the user to introduce energy decision-making into the earliest phases of the design process and facilitates access to the literature on pertinent issues and awareness of debates and issues on topics. The Guide focuses on individual technologies, as well as control systems, and important operational factors such as building commissioning. Most importantly, the Guide is designed to foster a systems perspective (e.g. “right sizing”) and to present current leading-edge design practices and principles.

Research Agenda

- We identify new ways to secure energy savings in laboratory-type facilities while simultaneously offering measurable improvements in the quality and non-energy performance of those facilities.

- We identify five major avenues of research that would serve to improve energy efficiency in California Laboratory-Type Facilities. These include: (1) Technology R&D; (2) Technology Transfer; (3) Additional Design Guide Development; (4) Design Guide Validation; and (5) Field Assessment of Additional Opportunities.

- We group the specific recommended research activities into three key (and complementary) areas: (1) Design Processes and Energy Data Diagnostics; (2) Technology and Systems Integration; and (3) Indoor Environmental Management and Control Strategies.

II. Introduction

Project Overview

The central aim of this project is to provide knowledge and tools for improving the energy efficiency and performance of new and existing laboratory-type facilities in California. We approach the task along three avenues: (1) identification of current energy use and savings potential, (2) development of *A Design Guide for Energy Efficient Research Laboratories*, and (3) development of a research agenda for focused technology development and for improving our understanding of the market.

An analysis of energy use in laboratory-type facilities is complicated by the fact that "laboratories" are not explicitly recognized in conventional energy statistics or Standard Industrial Code (SIC) classification systems and that energy & market data are often treated as highly proprietary. The activities included by this definition are diverse, including such building types as traditional laboratories, hospitals, and cleanrooms. Our definition includes research as well as production laboratories, and it includes private as well as publicly owned buildings. In our review of 253 standard industrial code (SIC) categories of energy users in California, we identified approximately 80 (about one third) as housing laboratory-type activities.

For the purposes of this study, "laboratory-type facilities" are buildings that contain areas where "isolated operations" are performed with hazardous/toxic or precious/delicate materials. This isolation is accomplished through the air balance/pressure relationship to adjacent areas. The pressure relationship is either negative for hazardous isolation for handling hazardous/toxic operations, or positive for protective isolation for handling precious/delicate operations.

Characteristics of the laboratory-type environment that are coupled tightly with energy use include ventilation rates, temperature requirements, humidity requirements, filtration efficiency, fume hoods, etc., that are directly related to the "isolated operations". Laboratory-type environments offer special energy challenges in the areas of technology, operations and maintenance, commissioning, diagnostics, design tools, indoor environment, and critical efficiency-productivity issues.

Research versus Production Laboratories

The distinction between laboratories intended for research and those intended for production is important from an energy standpoint. Research laboratories are common outside of academic or government settings. A listing of 150 high-tech construction projects in California during the 1990s indicated that one-third of all projects included research laboratory facilities.[1]

Operating patterns have important implications for energy use. Research laboratories (especially those located in university settings) have very irregular operating patterns, seasonally as well as diurnally. Because of this, the diversity of loads is of critical importance in design of HVAC systems. Energy management strategies based on control (of lighting, ventilation, etc.) offer particular promise in research laboratories where occupancy varies or the need for certain processes is sporadic.

Production laboratories, on the other hand, tend to be used very intensively. As a result, loads are relatively level. Around-the-clock operation is not uncommon, especially for cleanrooms where the importance of maintaining high-quality environmental conditions means that the ventilation is turned off only when absolutely necessary (even if there is a pause in the production process). Interruptions of production for the sake of energy-management interventions are far less acceptable in a (commercial) production laboratory where downtime is extremely costly.

Lastly, in production laboratories energy costs are very small in proportion to the value of production, while in research laboratories they can represent a relatively high share of total costs. At the energy-intensive end of the scale — cleanrooms with energy intensities of ~1000 kWh/ft^2-year — the energy cost of ~$100/ft^2-year is small compared to the e.g. $750 million value of the annual production of silicon wafers in a 30,000 square-foot facility (e.g. $25,000/ft^2-year).

This report focuses on both types of laboratory facilities. However, the Design Guide portion of the project covers only research laboratories.

California Laboratory-Type Facilities in Context

California laboratory-type facilities play a special role in the state's energy sector, and in the broader context of the State's economy. The presence and prosperity of hi-tech industry is a prime indicator of economic growth and, correspondingly, often serves as a driver of regional energy demand. As may be seen in virtually any sector, efficiency opportunities from applying existing and prospective technologies in laboratory-type facilities are substantial. That such opportunities go untapped suggests the presence of market barriers. These are discussed in Section V.

Laboratory-type facilities are much more energy-intensive than typical buildings in California, as illustrated in **Figures 2a & 2b**. As described below, we estimate the annual cost of energy used in laboratory-type facilities at $700 million for the year 1993, which represents 35% of the total in the sectors (manufacturing, electronics, academic, and healthcare) in which we expect to find such facilities.

Figure 2a

Comparative Electricity Use in California Buildings

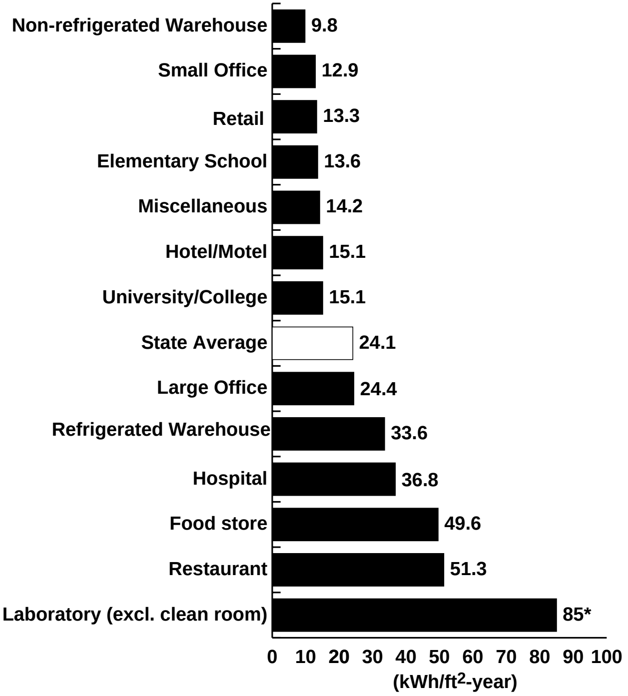
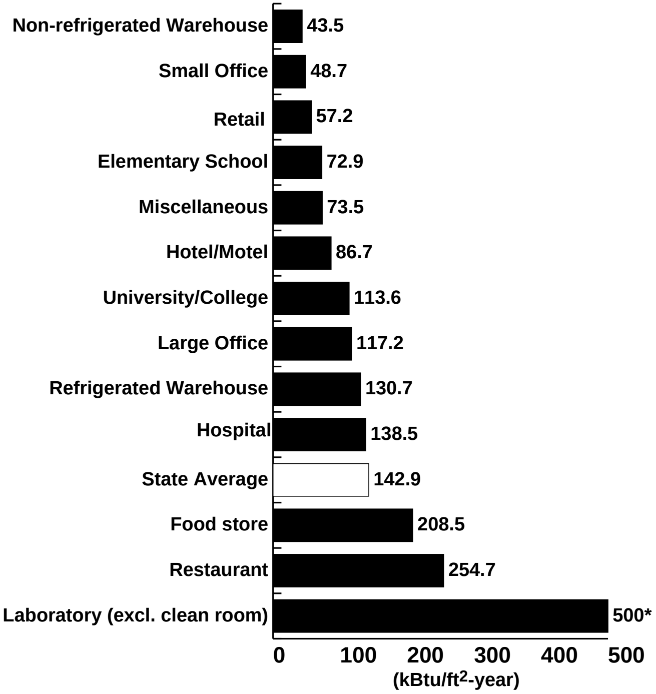


Figure 2b

Comparative Natural Gas Use in California Buildings



*Note: Building energy data are sales-weighted electricity intensities (a) and natural gas intensities (b) for PG&E, SCE, and SDG&E. Source: California Energy Commission (Ken Goeke); * LBNL estimates.*

Cleanrooms clearly represent a key segment of laboratory-type facilities. With hundreds of air changes per hour in some cases, the cleanest cleanrooms exhibit many times the energy intensity of normal commercial buildings. California represents 14% of the US cleanroom stock. California cleanrooms employ about 60,000 people and a very large market surrounding the construction and operations of cleanrooms.

III. Energy Use and Savings Potential in California Laboratory-Type Facilities

Data Availability

We conducted an exhaustive search for existing sources of data on energy use and stock characteristics for "laboratory-type" buildings in California. Because laboratory facilities are used so widely in many disciplines and industrial activities; because "laboratory" is a poorly defined term; and because SIC codes tend to classify economic activity in terms of product and service provided, rather than the environment in which they are provided, very little energy information specific to the laboratory environment is available. Compounding this problem, energy data for laboratory-type facilities is intensely protected as proprietary, perhaps more so than in any other sector.

The promising government sources (California Energy Commission, US Department of Energy/Energy Information Administration surveys [CBECS, MECS], Bureau of Census) tend not to treat laboratory-type facilities in isolation from other building types. The CEC provided very detailed statewide electricity and gas consumption data at the four-digit SIC level, and some end-use profiles at a higher level of aggregation. The CEC data also include floor area, employment, and shipment estimates (at a relatively high SIC level), with projections to the year 2015.

The CBECS survey contains a category entitled "other", which includes laboratory buildings. EIA performed some special data processing for this project in an attempt to isolate information on laboratory buildings. The data could not be disaggregated to the State level and so EIA prepared a series of crosstabs at the West Pacific Census Division level. Unfortunately, even at this higher level of aggregation, there were too few laboratories in their database to provide statistically significant results.[2] EIA also isolated their statistics on healthcare for the region, but the results were often statistically insignificant below the level of detail already available from in-state sources such as the California Energy Commission.

Data reported in DOE's Manufacturing Energy Consumption Survey are maintained by the Census Bureau. MECS staff declined to extract laboratory-related data, citing constraints imposed by the structure of their database and concern about confidentiality agreements with businesses that respond to their survey.

The Department of Commerce database of manufacturing is disaggregated by SIC code. There is no 4-digit SIC code for laboratory-type facilities. The data are not disaggregated by state. The lowest level of resolution in this database is Census Division.

An electronic search of the University of California library system, including Current Contents, CCT, and ABI-Inform resulted in no useful references.

We investigated the possibility that there existed comprehensive lists of industrial facilities classified by the Uniform Building Code as H6 and H7 (hazardous laboratory spaces and semiconductor manufacturing space). However, the UBC is enforced at the municipal and county levels, not by the state of California, so any effort to collect H6-7 floor area data would require acquisition of this information city by city and county by county and then aggregation to the state level.

We also sought energy and stock characteristics data from a variety of private-sector sources, but prospective sources either had no pertinent data or treated such data as proprietary and confidential. The following industry organizations were contacted:

- SAMA (Scientific Apparatus Makers Association)
- Instrument Society of America
- American Council of Independent Laboratories
- American Association for Laboratory Accreditation
- American Electronics Association
- Semiconductor Industry Association
- SEMATECH and SEMI (Semiconductor Equipment and Materials International)
- The American Association for Laboratory Accreditation and SEMATEC (the chip manufacturing consortium)

We contacted each of the major California utilities and the Electric Power Research Institute (EPRI), but no laboratory-specific data were identified. This is somewhat remarkable given the enormous energy and peak power demand represented by this customer segment. It is likely that relevant information exists in the utilities' "gray literature" reports, which tend not to be available outside the companies.

Detailed data for five major University of California campuses were acquired, based on extensive energy audits conducted for the purposes of utility cost allocation to specific buildings. These data provide a rich profile of information on energy use and floor area in laboratory-type facilities in the UC system.

Cleanrooms are an extremely important building type in the context of this project. We contacted a number of trade organizations and obtained a number of publications from the electronics industry, (the largest user of cleanrooms in California) in search of energy use, manufacturing floor area and employment data, and growth forecasts. Several of the above-listed organizations were contacted, as well as Cleanrooms and Microcontamination magazines. These organizations either do not collect energy statistics from their members, or were not willing to share it with a non-member entity. We acquired from the McIlvaine Company a detailed information database on the U.S. cleanroom industry, including statistics specific to California. The materials include product information, floor area statistics, and market data. Although the majority of cleanroom use is in the semiconductor, electronics and biotechnology industries, an interesting set of smaller industries do as well, including fine instrument manufacturing and yogurt/long-life dairy products. Using these data sources, we developed a model to compute statewide energy use in cleanrooms.

Dodge construction reports formerly contained some information on renovation of various types of industrial facilities such as lab spaces. However they are no longer being published.

We were also able to obtain detailed energy use and floor area estimates for the U.S. Department of Energy's major laboratory facilities in California.
The result of our reconnaissance is that the best available data are those from the CEC, McIlvaine (on cleanrooms only), and from a special study of laboratory energy in the UC system. These sources provided the basis for us to estimate laboratory-type energy use in the state, as described in the following section. None of the sources examined provide load-shape or end-use analysis of laboratory-type facilities. To do so would require extensive simulation or submetering studies.

Statewide Laboratory Energy Use

We have gathered and reviewed state-level gas and electric data for 253 SIC-code categories (4-digit level in most cases, ranging from 2700-8734). These consumer categories represent energy users who potentially conduct activities in laboratory-type environments. These customer segments span the food products, printing and publishing, chemicals, pharmaceuticals, electronic equipment, electronic consumer products, education, and healthcare sectors. (We excluded the food products sectors because laboratory-type production environments therein are still relatively rare.)

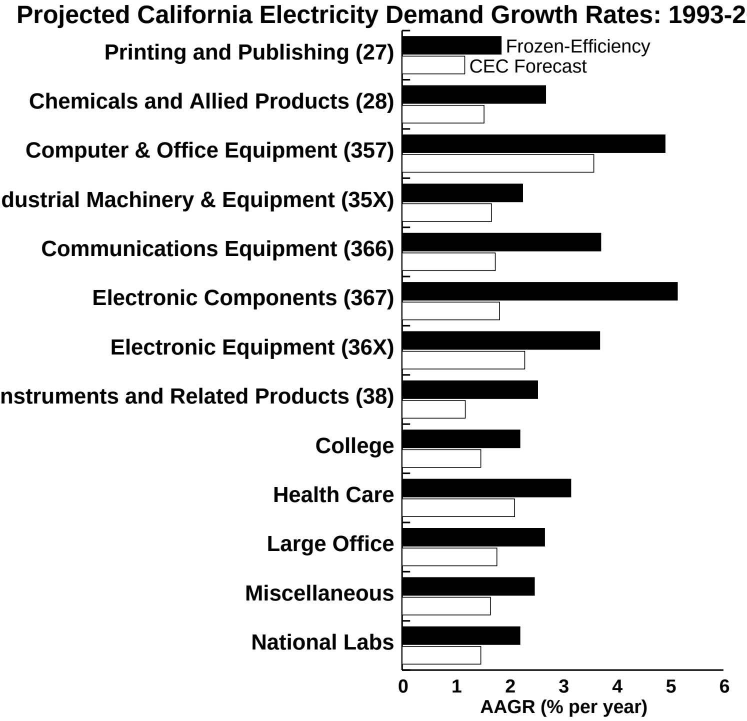
We identified specific customer segments that (i) are predominantly laboratory-type facilities, and (ii) those that contain significant laboratory and non-laboratory spaces (**Appendix A**). For the first group (i) we allocated all energy use to the laboratory-type category and for the second group (ii) we counted one-third of the energy use as “laboratory-related”. Due to the relatively high energy-intensity of laboratory environments, the one-third estimate implies a significantly lower proportion of floor area actually dedicated to laboratory-type spaces. This corresponds to approximately 8% of total floor area for cases such as those we studied in detail for the University of California segment (i.e. where energy intensities of 85 kWh/ft^2-year in laboratory-type buildings are typically four-times higher on average than in non-laboratory type spaces). In the case of cleanrooms, the average electricity intensity of 600 kWh/ft^2-year is ~30-times higher than typical buildings.

To this SIC-based estimated we added specific detailed estimates of laboratory-type facility energy use on major UC campuses, cleanrooms, and national laboratories. With these two sets of values we developed an estimate of the actual laboratory-type energy use in California.

The results suggest that roughly one third of the total energy use over the entire group of consumers represented by the 253 SIC codes is attributable to laboratory-type facilities, i.e. 111 x 10^{12} source BTUs and an average 2.1 GW electrical capacity.

The California Energy Commission provided energy demand forecasts by SIC category and major end use to the year 2015. They also provided forecast data on shipments for each sector, which we take as a proxy for the growth in demand for energy services and as a basis for our “frozen efficiency” demand scenario. The growth rates are summarized in **Figure 3** and the absolute current and projected energy demand in **Figure 4**. The key segments containing laboratory-type facilities (SIC categories 357-38, colleges, and healthcare) have projected demand growth rates in excess of most other segments, including large office buildings. In several important cases, natural gas is projected to grow more quickly than electricity. Of the key segments, natural gas is only significant for colleges and healthcare.

Figure 3



Note: The baseline values reflect current CEC forecasts for specific SIC customer categories. Frozen efficiency is set equal to the CEC forecast for shipments from each SIC category. The value for national laboratories set equal to the CEC rates for colleges and universities. Source: CEC data provided by Tom Gorin.

Figure 4a

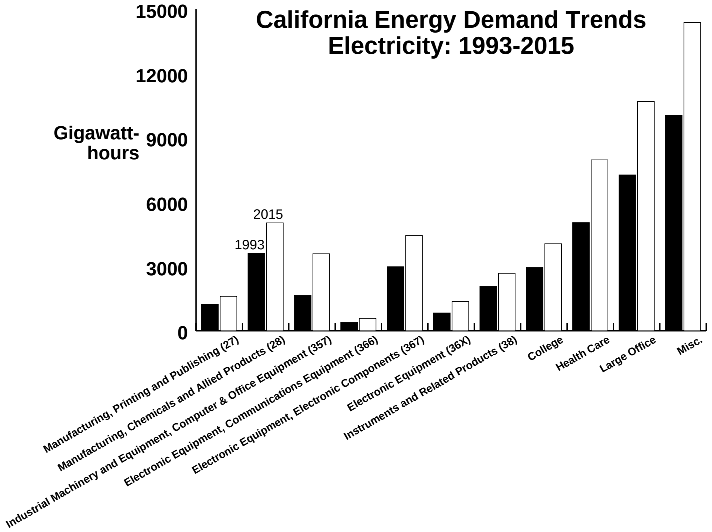
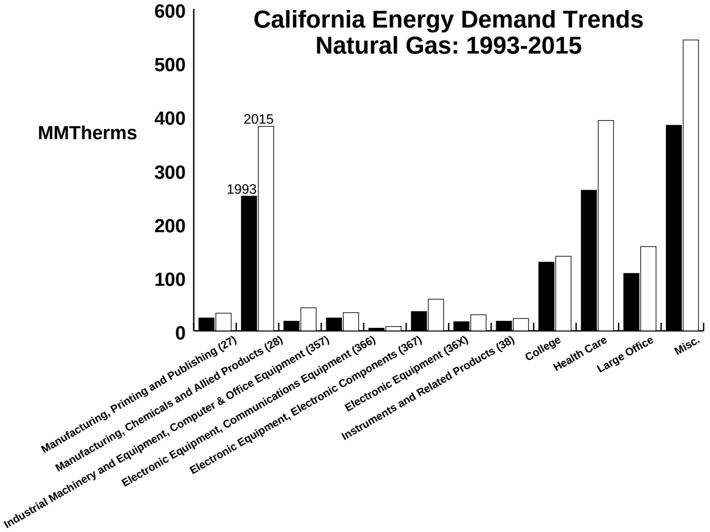


Figure 4b



Note: Projected California energy demand by SIC code for segments containing laboratory-type facilities: 1993-2015 — Electricity (a) and Natural Gas (b). Source: California Energy Commission

Applying the sector-specific demand growth rates from the CEC forecast results in a growth in total primary energy in laboratory-type facilities of 58% by the year 2015 (**Table 1**). Electricity demand increases by 60%, and natural gas by 49%.

Table 1. Summary of Estimated Laboratory-Type Energy Use in California.

Frozen-Efficiency Forecast: 2015	Total 1993	Energy Cost ($M)	Total 2015	Energy Cost ($M)	Percent Growth	Annual Growth Rate
Total Energy (TBTU)	111	700	*255*	1640	131%	3.9%
Electricity Consumption (GWh)	8774	644	*20782*	1525	137%	4.0%
Electrical Generating Capacity (GW)	2.1		*4.9*		137%	4.0%
Natural Gas (TBTU)	21	56	*43*	116	106%	3.3%
CEC Baseline Forecast: 2015						
Total Energy (TBTU)			*174*	1108	58%	2.1%
Electricity Consumption (GWh)			*13949*	1023	60%	2.2%
Electrical Generating Capacity (GW)			*3.3*		60%	2.2%
Natural Gas (TBTU)			*31*	84	49%	1.8%
Efficiency Forecast: 2015						
Total Energy (TBTU)			*128*	820	16%	0.7%
Electricity Consumption (GWh)			*10391*	762	18%	0.8%
Electrical Generating Capacity (GW)			*2.5*		18%	0.8%
Natural Gas (TBTU)			*21*	58	3%	0.1%
Annual Savings vs. Frozen Efficiency: 2015			*Total*	*Energy Cost ($M)*		
Total Energy (TBTU)			128	820		
Electricity (GWh)			10391	762		
Electrical Generating Capacity (GW)			2.5			
Natural Gas (TBTU)			21	58		

Note: Derivation of baseyear values shown in Appendix A.

The CEC also provided projected floor area and employment levels by SIC category (**Table 2**). The sectors most relevant to this study (SIC 27-39) represent over 400,000 jobs. Employment and floor area are projected to decline in most instances, whereas energy demand is projected to grow. This is attributable to increasing intensity of activity and production rates in existing facilities. We identified baseyear floor area statistics for cleanrooms, University of California laboratory facilities, and national laboratories located in the state. For other segments, we estimated the floor area based on assumed energy intensity of 85 kWh/sq.ft.-year and total energy use. Cleanrooms represent 12% of total floor area, Universities 8%, national laboratories 5%, healthcare 31%, and “other” 44%. Due to significantly higher energy intensities in cleanrooms, they are responsible for a disproportionate share of total energy demand, estimated at 54% (**Figure 5**).

Figure 5

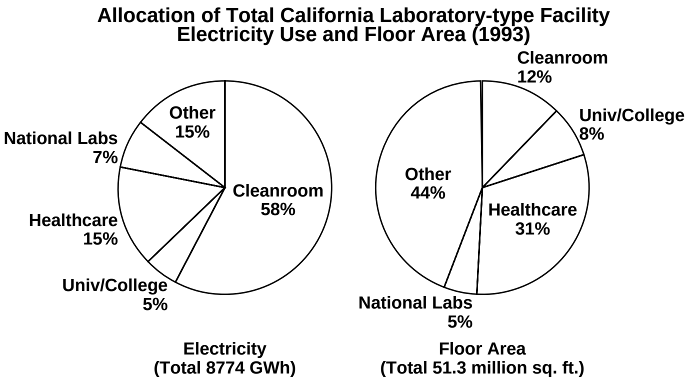


Table 2. California Industry Employment and Floorspace Forecasts.

Employment (thousands of jobs) SIC	Code Description	1993	2000	2007	2015	Average Annual Growth Rate
20X	Food Products	110	109	106	97	-0.58%
22	Textile Mill Products	15	16	14	12	-1.20%
23	Apparel & Other Products	138	159	157	138	0.01%
25	Furniture and Fixtures	54	57	57	54	-0.03%
26X	Paper & Allied Products	34	35	34	31	-0.45%
27	Printing & Publishing	151	162	173	177	0.73%
28	Chemicals & Allied Products	73	78	77	71	-0.13%
308	Miscellaneous Plastic Products, NEC	59	70	75	75	1.06%
30X	Rubber & Misc. Plastic Products	14	16	14	13	-0.20%
32X	Stone, Clay, Glass Products	29	31	30	28	-0.13%
33	Primary Metal Industries	39	39	35	29	-1.38%
34	Fabricated Metal Products	125	132	129	120	-0.20%
357	Industrial Equipment, Computer & Office Equipment	90	89	96	87	-0.12%
35X	Industrial Machinery and Equipment	102	108	105	95	-0.32%
366	Electronic Equipment, Communications Equipment	29	30	30	28	-0.18%
367	Electronic Equipment, Electronic Components	114	119	125	110	-0.19%
36X	Electronic & Electric Equipment	78	82	83	78	-0.04%
37	Transportation Equipment	273	229	223	197	-1.47%
38	Instruments & Related Products	215	196	200	187	-0.64%
39	Miscellaneous Manufacturing Industries	34	33	28	23	-1.85%
Total		**1777**	**1787**	**1792**	**1647**	**-0.34%**
Floorspace (millions of square feet)						
20X	Food Products	65.7	64.9	63.6	57.8	-0.58%
22	Textile Mill Products	6.2	6.2	5.8	4.8	-1.20%
23	Apparel & Textile Products	36.2	41.8	41.2	36.3	0.01%
25	Furniture and Fixtures	33.9	35.5	35.9	33.7	-0.03%
26X	Paper & Allied Products	21.9	22.7	21.9	19.9	-0.45%
27	Printing & Publishing	54.7	58.8	62.9	64.3	0.73%
28	Chemical Products	47.4	50.8	49.9	46.1	-0.13%
308	Misc. Plastic Products	38.4	45.0	48.6	48.4	1.06%
30X	Rubber & Plastics	4.7	5.2	4.8	4.5	-0.20%
32X	Stone, Clay & Glass Products	15.8	16.6	16.5	15.4	-0.13%
33	Primary Metal Industries	10.8	10.7	9.6	7.9	-1.38%
34	Fabricated Metal Products	59.5	62.9	61.6	56.9	-0.20%
357	Computer & Office Equipment	37.4	37.2	40.2	36.4	-0.12%
35X	Industrial Equipment	42.7	45.1	43.9	39.8	-0.32%
366	Communications Equipment	7.3	7.7	7.6	7.1	-0.18%
367	Electronic Components	29.1	30.3	31.8	27.9	-0.19%
36X	Electronic & Electric Equipment	20.0	21.0	21.1	19.8	-0.04%
37	Transportation Equipment	80.1	67.2	65.2	57.8	-1.47%
38	Instruments & Related Products	54.4	49.5	50.7	47.3	-0.64%
39	Misc. Industries	14.7	14.1	12.0	9.7	-1.85%
Total		**681**	**693**	**695**	**642**	**-0.27%**

Source: California Energy Commission

Statewide Laboratory Energy Savings Potential

We developed energy savings potential estimates for new and existing laboratory-type facilities. These are based on specific case studies as well as a design philosophy presented in the companion document to this report entitled *A Design Guide for Energy-Efficient Research Facilities*.

In order to estimate energy savings opportunities in new buildings, we examined the energy intensities of twelve newly-constructed laboratory buildings representing 165,000 square feet, at various UC Campuses and a variety of laboratories at LBNL (representing 225,000 square feet in seven buildings). We also obtained combined audit/simulation data representing the entire population of laboratory-type facilities at five major campuses in the UC system (4 million square feet). Based on these data sources, we have adopted estimates of 85 kWh/ft^2-year (20 W/ft^2) for electricity use in typical new laboratory-type buildings and 5 therms/ft^2 for natural gas use.

Electric values for cleanrooms can be up to twelve-times higher, depending on the Classification. We develop separate estimates for cleanrooms in Section IV below.

Our experience to-date with a major laboratory energy management program at Lawrence Berkeley National Laboratory includes the achievement of 40% site-wide energy savings in the retrofit of laboratory-type buildings (i.e. laboratory spaces as well as general non-laboratory spaces).[3] This represents only very partial retrofit of all eligible facilities, commercially available technologies, and investments with a ~5-year payback constraint. (Even though new government laboratory buildings are required to minimize life-cycle costs, time and budget constraints normally prevent design teams from achieving this goal.) As described below, DOE has achieved 43% savings throughout 120 million square feet of floor area, much of which represents laboratory-type facilities.

For ordinary types of laboratories, we estimate the potential for retrofit savings at 50%, which corresponds to 685 kBtu/sq.ft.-year (source energy) and 10 W/sq.ft. in avoided electrical capacity (assuming a 48% electrical generating capacity factor, the sales-weighted average for the state's major utilities). If cleanrooms, which are far more energy-intensive, are averaged into the statewide total, the savings estimates rise to 1100 kBtu/ft^2-year and 20 watts/sf, respectively

Our experience with new construction shows on the one hand a lower percentage savings than assumed for retrofit, because existing building codes already ensure a considerable degree of savings beyond typical practice predating the codes. On the other hand, certain measures not feasible in existing buildings are possible in new construction. Often, retrofit opportunities exist upon completion of new buildings that have ostensibly been designed to be energy-efficient. One laboratory building at LBNL, completed in 1987, is undergoing a comprehensive retrofit (lighting, controls, motor drives, fume hood controls, etc.) to save an estimated 85% of its gas and 60% of its electricity consumption at a project cost of $710,000, resulting in a 7-year simple payback period. Another LBNL lab building, completed in 1989, is being retrofitted for an estimated 77% gas and 44% electricity savings from a $380,000 retrofit project (HVAC controls, some lighting and motor drives), plus several operational changes and program-funded modifications, yielding a 6-year payback overall. For the purposes of this study, we estimate the potential for new construction at 50%.

Our savings estimates include savings from discrete technologies as well as significant attention to right-sizing, operations and maintenance improvements and commissioning. However, the savings estimates we have adopted do not reflect achieving theoretical ideals, nor total market penetration, but rather maximum feasible market penetration assuming a substantial market transformation occurs. The best technology/approach is not assumed to be chosen consistently in all new construction or in retrofit applications. For example, as described in Appendix B, we estimate the maximum efficiency potential in cleanrooms at 80%.

We estimated the statewide energy savings potential in laboratory-type facilities by applying our proportionate savings estimates to the frozen-efficiency baseline estimate of laboratory energy use developed above (see **Appendix A**). This results in a savings potential (by the year 2015) of 128 TBTUs, including 10.4 billion kilowatt-hours of electricity (2500 megawatts) and 21 TBTUs of natural gas, valued at $820 million/year. [The corresponding "overnight" savings potential (i.e. for existing buildings only, excluding floorspace growth) is 55 TBTU of source energy and 1050 megawatts].

The statewide results for the frozen efficiency scenario, CEC forecast, and high-efficiency scenario are presented **in Figures 6a and 6b**. Note that the CEC does not itself generate a forecast for laboratory energy demand; rather, we apply official CEC growth rates for each SIC group to the estimate of laboratory energy demand developed in Appendix A.

Figure 6a

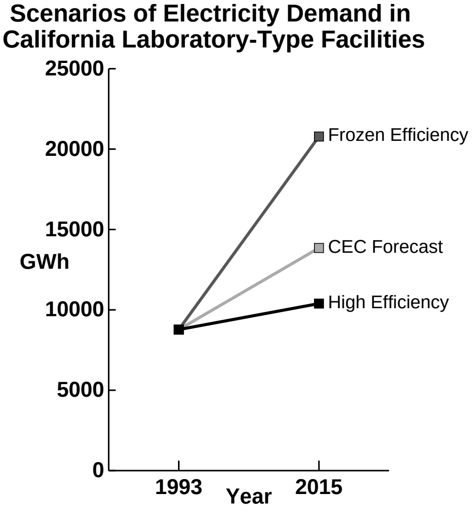
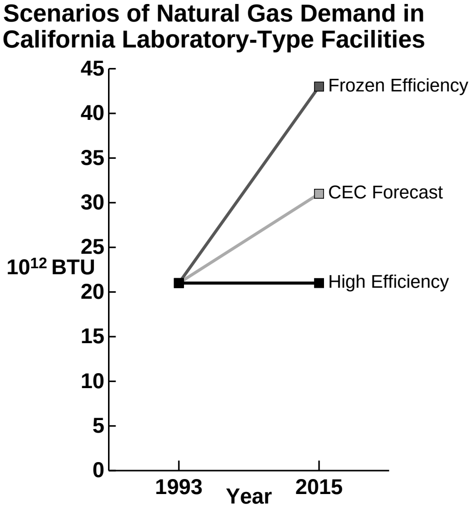


Figure 6b



Building Stock Retirement and Retrofit Potential

Retirement and renovation rates for laboratory-type facilities are rarely reported in the literature. According to the McIlvaine Company (the best source of data on the U.S. cleanroom market), Class 1-10 semiconductor cleanrooms are used for only three to five years and then retired entirely from that use. This suggests a rate of retrofit opportunity that substantially exceeds that encountered in the non-laboratory sector. Other types of cleanrooms are retired at a rate of approximately 5%/year, still more rapidly than is the case for typical buildings.

For the time horizon used in this study (1993-2015) we assume that virtually the entire stock has been retired or has undergone major renovations and equipment replacements that afford an opportunity for comprehensive retrofit.

Results for Specific Sectors and Fuels

- Four "sectors" represent ~80% of total statewide laboratory-type energy use. These are healthcare, colleges and universities, national laboratories, and cleanrooms. Efforts to build a continuing R&D program in this area should look for specific opportunities in these sectors.
- Laboratory type facilities within the healthcare sector represent 14% of statewide electricity use in laboratories.

- National laboratories represent 2.6 million square feet of floor are, 650 GWh of electricity use, and 700 x 10^9 BTUs of fuel. Energy use at the three sites represents 7% of laboratory-type energy use in California.
- Of over 16 million square feet of University of California floor area reviewed, 25% is allocated to laboratories. Energy intensities were four-times higher on average in laboratories than in non-laboratory buildings, and lab energy use represents 58% of campus-wide energy consumption. University laboratory energy use represents approximately 5% of total statewide laboratory-type facility electricity use.
- California cleanrooms are an especially significant energy-intensive segment, representing 14% of the U.S. total cleanroom stock. California cleanroom floor area is estimated at 6.3 million square feet (Class 1-100,000), with approximately one half in the especially energy-intensive Class 1-100 category. These values exclude a large variety of non-traditional uses of cleanrooms — e.g. automotive spray-painting and yogurt making — which are today small but are anticipated to grow significantly in the coming years. Cleanroom floor area in California is forecast to grow by 2.5-fold to 15 million square feet by the year 2015. Our estimates indicate current cleanroom energy use equal to about 5 BkWh and 1200 MW (see Section IV), represents 54% of the statewide total for laboratory-type faculty.
- Natural gas is a significant energy source in laboratory-type facilities, as illustrated by its ~30% of total site energy use in 7 LBNL labs and 40% share in 12 new UC labs. Statewide, we estimate that gas represents 20% of total source energy use in laboratory-type facilities.

IV. Detailed Sub-Sector Assessments

Cleanrooms

Cleanrooms are specially constructed enclosed areas that are environmentally controlled with respect to airborne particulates, temperature, humidity, air flow patterns, air motion, and lighting. They are sealed facilities with specialized air handling and filtration systems designed to minimize static electricity or the concentrations of particles and other contaminants that may interfere with scientific research, manufacturing, medical operations and other activities. Typically, cleanrooms produce a vertical laminar flow of air throughout a large area of the space. The air is filtered, and contaminants are purged through large air flow. Because of the need to control air velocities, as well as regulate other environmental factors within tightly prescribed limits, cleanrooms are large users of energy, and they present commensurate opportunities to improve efficiency.

Cleanrooms are usually defined in terms of “classes”, representing the maximum number of particles in a defined volume of air. There are six classes, Class 1, 10, 100, 1,000, 10,000 and 100,000. The designation refers to the number of particles greater than or equal to 0.5 micrometers (microns) per cubic foot of air. Thus, in a Class 100 cleanroom there can be no more than 100 particles of this size per cubic foot. Subclass 1 cleanrooms are now coming into use, and are the most energy-intensive of all cleanroom types.

Table 3 describes the classes of cleanroom and their typical applications. **Table 4** lists the SIC codes of 37 industry segments that use cleanrooms. Cleanrooms are currently used in connection with hundreds of products or processes.

Table 3. Cleanroom classes and typical applications.

Class	*Typical application*
1	integrated circuit manufacturing, sub-micron scale
10	integrated circuit manufacturing, two microns or below; allograft tissue processing
100	manufacture of injectible medicines; aseptic pharmaceutical packaging; selected surgical operations and other hospital functions; integrated circuit manufacturing; dairy products; isolation of immunosuppressed patients
1,000	high-quality optical equipment; assembly of precision instruments; assembly of miniturized bearings
10,000	precision hydraulic/pneumatic equipment assembly, precision timing devices; high-grade gearing; servo-control valves
100,000	general optical work; electronic device and component assembly; hydraulic/pneumatic assembly; printing and photographic work

Table 4. SIC Codes for Industries that use cleanrooms.

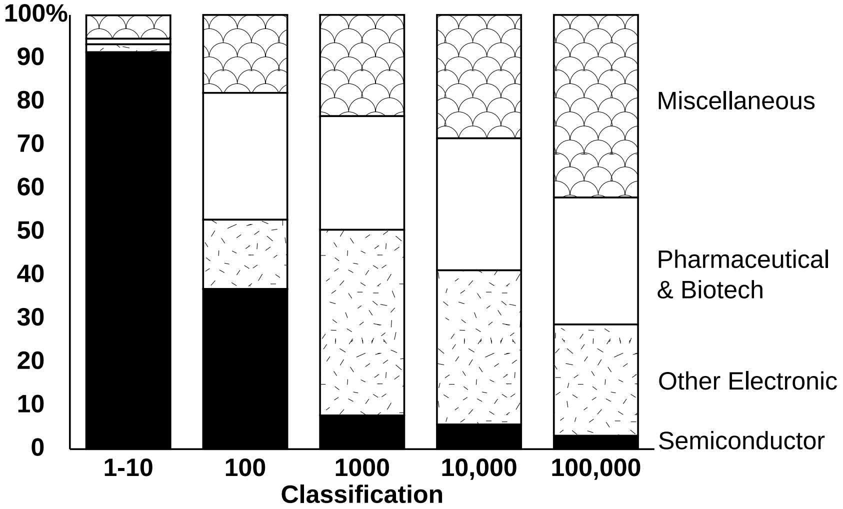
202		dairy industry	3669	*	other
2026		milk and yogurt	367		electronic components and accessories
203		canned, frozen and preserved food	3671		electron tubes
275		commercial printing	3672		printed circuit boards
283		pharmaceuticals	3674		semiconductor devices
2833		medical chemicals	3695	*	magnetic and optical recording media
2834		pharmaceutical preparations	3711		automotive manufacturing (spary painting)
2835		in-vitro preparations	38	*	instruments
2836		biological products	3812	*	navigation instruments
357	*	computer and office equipment	3823	*	industrial instruments
3571	*	electronic computers	3827	*	optical instruments
3572	*	computer storage devices	3841	*	surgical and medical
3575	*	computer terminals	3851	*	ophthalmic goods
3577	*	computer peripherals	3861	*	photographic goods
3578	*	calculating and accounting	3873	*	clocks and watches
3579	*	office machines	8221	*	universities and colleges
366	*	communication equipment	8062		general medical and surgical hospitals
3661	*	telephones	8071		medical laboratories
3663	*	radio & TV			

** cleanroom data for these sectors not included in McIlvaine estimates.*

Figure 7 characterizes the U.S. cleanroom market, both in terms of distribution according to classification and according to major industry segment. While Class 100,000 represents the largest segment in terms of floor area it is far less energy-intensive than the higher classes. The fastest-growing type is also the most energy-intensive type (Class 1-10), and within this Class floor area is projected to grow most quickly in the Pharmaceutical/Biotechnology segment. The fastest growing industry segment is the miscellaneous category, which includes non-traditional applications of cleanrooms, as described below. No analogous data are available for California, but the qualitative trends are likely to be similar. The miscellaneous category is apportioned approximately as follows: 20% aerospace, 20% food, 20% hospital and medical devices, and 40% other.[4]

Figure 7

U.S. Cleanroom Type by Industry Segment: 1991



Cleanrooms in Manufacturing Settings

In manufacturing settings, cleanrooms are most commonly associated with the production of semiconductor-based integrated circuits and other electronic components, and with the pharmaceutical and biotechnology industry. The latter includes the manufacture of traditional pharmaceuticals, biotechnology-derived products, and the aseptic (sterile) packaging of these products. Together, these industries account for more than 70% of the cleanroom square footage in the U.S. The IC manufacturers in particular require the highest standards of cleanliness, and are most heavily associated with efforts to advance the state of the art beyond the Class 1 level.

However, other industries also use cleanrooms of less rigorous cleanliness levels. Instrumentation manufacture, including fine optical, navigation, and aerospace components and systems, require clean conditions as do standards laboratories, photographic developing and high quality printing. In addition to integrated circuits, the manufacture of electronic devices such as circuit boards, disk drives, flat panel displays, computers, and consumer electronics require clean conditions. Chemical manufacturing requires cleanliness to make high-purity chemicals and metals. Automobile manufacturers are using cleanroom conditions increasingly to produce high-quality paint finishes on their cars, as well as more defect-free parts.

Cleanrooms are increasingly used in the food industry. Long shelf-life dairy products such as milk and yogurt, often stored at room temperatures in groceries, have been common in Europe for years, and their popularity is growing in the U.S. The manufacture of these products requires clean conditions to keep the products free of pathogenic bacteria. Cleanrooms also have applications in other types of food processing, such as orange juice, meat packing, and chilled foods.

Cleanrooms in Hospitals

Cleanrooms are used in hospital operating rooms, and other healthcare environments ranging from burn wards to intensive care rooms to delivery rooms. The focus in these environments is to control patient and worker exposure to bacteria and viruses. Hospital cleanroom standards for bacterial exposure are often expressed as colony forming units (CFUs) per unit volume. CFUs are usually larger than one micron, and they are effectively controlled by HEPA (high-efficiency particulate air) filters. Viral particles are much smaller, ranging from 0.003 to 0.05 microns; no filters are known to be effective against viruses.

People in hospitals typically emit 1,000 CFUs per person per minute. HEPA filtration air with a mixed flow pattern and 10 to 15 air changes per hour can reduce ambient levels to 200 CFUs/m^3 of air. HEPA-filtered laminar-flow air can reduce these levels considerably, to 10 CFUs/m^3. Hospitals generally aim for Class 100 conditions in operating rooms, and cleanroom conditions are increasingly being sought for other types of hospital environments as well. **Table 5** provides an example of hospital cleanroom standards developed by the Swiss Hospitals Institute.

Table 5. An example of hospital cleanroom standards

Class	Level of cleanliness (CFUs/m^2)	Applications
1	<=10	Special operating theaters for transplants, orthopedic, bone or heart surgery; burn wards; intensive care for immunosuppressive treatment; leukemia therapy; serum processing.
2	50 to 200	Typical operating theaters, including accident surgery; premature baby and perinatal care; intensive care for surgical and internal cases; burn wards.
3	200 to 500; = outside air's germ level	Intensive care for coronary patients, delivery rooms; nursing, recovery and emergency wards; rooms for examination and minor operations.
4	patient rooms with contaminated air	Infection wards; isotope treatment.
5	other rooms	Lavatories; cleaning rooms; mortuary rooms.

Source: The McIlvaine Company, "Cleanrooms 1992-2000"

Cleanroom conditions are expanding in hospitals because more and more applications are being recognized as needing them, like orthopedic surgery (and other lengthy surgical procedures) and isolation of very contagious patients. The actual cleanliness required in hospital operating rooms varies considerably according to the kind of surgery.

Cleanroom Statistics for California

California has 6.3 million square feet of cleanroom space, representing 14% of the U.S. total, the second largest in the U.S. after Texas. The large stock of cleanroom space in California produces a proportionally large output of manufactured goods, primarily in electronics, especially semiconductors, and pharmaceuticals. California is the nation's largest manufacturer of electronics, exceeding in size the next closest state (New York) by a factor of two, and is the largest purchaser of cleanroom components. California's projected share of total cleanroom floor area drops from 14% in 1993 to 9% in 2015, but the net floor area in California continues to increase to about 15 million ft^2 in 2015.[5]

Cleanrooms are an exceptionally important segment of laboratory-type facilities in California, representing 61,000 jobs across the State[6]. With cleanroom component sales of $104 million, California represented about 15% of the total U.S. market in 1993. The single biggest component of the California total is HVAC equipment, at $44 million in 1993. Typical construction costs are $1000/square foot for Class 1-10 rooms. (Complete cleanrooms, including all process and monitoring equipment are considerably more costly—a typical semiconductor wafer fab can cost nearly $1 billion (20,000 square feet, or $5000/square foot)).

The McIlvaine data omit certain industrial activities that take place in cleanrooms (**Table 4**). Some manufacturing activities in SIC codes 38 (instruments) and 35 (computer and office equipment) require some degree of cleanroom conditions. Among the manufacturers included in these categories are navigational, optical and photographic instruments (under SIC 38) and high-capacity disk drives (SIC 35). Although these activities are not reflected in the McIlvaine data, they represent an extremely small percentage of the total cleanroom activity. McIlvaine estimates that 75% to 80% of California activity is accounted for by the manufacture of semiconductors and electronic components, and pharmaceuticals, either in biotechnology or the aseptic packaging of drugs. Remaining percentages amount to no more than 5% each for such categories as long-shelf-life dairy products, instruments, and electronic office equipment not semiconductors and electronic components.

Cleanroom Design, Energy Use, and Efficiency Potential

The forced circulation of air through cleanrooms is an important energy end use and an opportunity for improved energy efficiency. High air change rates and the use of HEPA and ultra-low penetration air (ULPA) filters to maintain high levels of cleanliness create considerable energy demand. The number of air changes per hour can very from several dozen, to as high as six or seven hundred in the cleanest environments. At high levels of air circulation, additional energy is required to maintain constant temperature and humidity.

We identified measures to decrease energy use in cleanrooms[7] and developed a model of cleanroom HVAC energy intensity and consumption (**Appendix B**). We estimate that cleanrooms in California used five billion kilowatt hours of electricity in 1993, corresponding to 1200 MW of electrical generating capacity. Given the essentially continuous operation of cleanrooms, this load is a good approximation of the simultaneous demand on utility generating resources. These estimates reflect HVAC energy use, but do not include energy used by the processes going on within the cleanrooms. Such processes are highly varied in their nature and in their energy intensity.

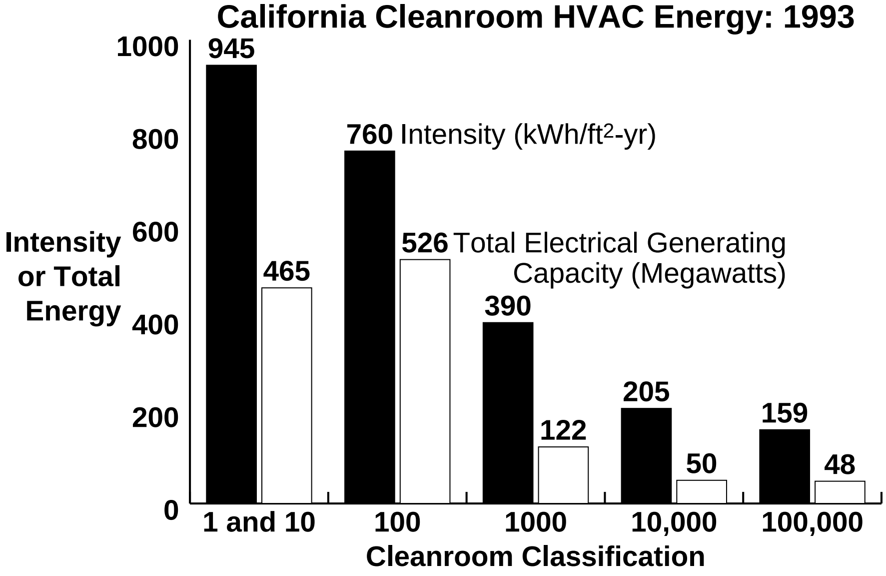
As shown in **Table 6 and Figure 8**, Class 1-10 and 100 cleanrooms have comparable importance in terms of contribution to statewide energy demand, and together represent about 90% of cleanroom HVAC energy. Electricity intensities range from 160 kWh/sq. ft. to 945 kWh/sq. ft., depending on Class (up to 100-times that of typical buildings). Heating energy use (e.g. natural gas) is 5- to 10-times that of non-laboratory buildings. Our derivation of cleanroom energy use is presented in Appendix B (**Table B-1**).

Table 6. Energy Use in California Clean Rooms.

	Cleanroom Class					**Totals or**
	1 and 10	100	1000	10000	100000	**Averages**
California floor space million ft^2	1.42	2.01	0.96	0.83	1.10	**6.32**
Calif floorspace, frac. of US market	30%	20%	10%	10%	10%	**14%**
Air Changes per Hour [8-foot ceiling]	675	525	225	75	38	**369**
Total CFM (10^6)	128	141	29	8	5	**311**
Fan Power (W/ft2)	96	74	32	11	5	**52**
Fan Energy (kWh/ft^2-year)	832	647	277	92	46	**455**
Heating therms/yr-ft^2	9.13	9.13	9.13	9.13	9.13	**9.13**
Cooling kWh/yr-ft^2	113	113	113	113	113	**113**
Total Electricity Intensity (Fan + Cooling), [kWh/ft^2-year]	945	760	390	205	159	**568**
Total Energy (MW, incl CA avg. 48% capacity factor)	465	526	122	50	48	**1211**
Total Energy (GWh)	1944	2198	509	210	200	**5061**

See Appendix B for derivation.

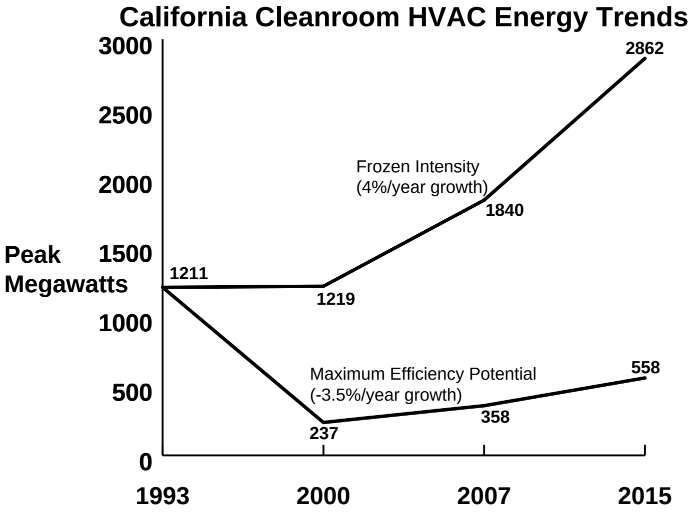
Figure 8



The future development of cleanroom energy demand is a function of many factors. Process changes (such as the trend towards minienvironments) will tend to push energy intensities down and trends in out-of-state and overseas markets could contribute to a major shift of cleanroom-type tasks out of California. However, many structural trends will contribute towards growing numbers of cleanrooms. These include increased use of Subclass 1 cleanrooms, new applications (e.g. in the food sector), and increasingly stringent demands on health and safety conditions in healthcare and manufacturing environments.

We developed a frozen-efficiency baseline forecast for cleanrooms in California, based on 4%/year average growth in floor area estimated by McIlvaine to the year 2015 (**Figure 9**). We do not attempt to incorporate any structural shift among the types of cleanrooms (although the likely scenario is a shift towards the more energy-intensive Classes). Applying the energy-efficiency potential derived in Appendix B, energy savings of 2000 megawatts by the year 2015 are obtained.

Figure 9



Note: Maximum potential savings estimated at 80% (versus market potential of 50% for all types of laboratory facilities assumed in the statewide savings estimate developed in Appendix A).

University-Based Laboratory Facilities

An excellent repository of data is available for assessing the energy used in laboratory-type buildings in the University of California system. Detailed studies were performed by one of us (Marton) during the mid-1980s to early-1990s for the purposes of enabling the universities to accurately recharge master-metered energy use to specific buildings. The sites studied include the campuses at Los Angeles, Berkeley, San Diego, Irvine, and San Francisco.[8]

The methodology is based on the extensive survey and analysis of random samples of rooms in university laboratories. Rooms included in the studies were divided into categories by such criteria as function, type of activity and type and magnitude of energy usage. Every assignable room was sorted into one of these categories, and the electricity and fossil fuel consumption and costs per assignable unit floor area were determined for each room category based on the survey and simulation analysis of randomly selected sample rooms.

Many thousands of rooms were audited in order to achieve a statistically-significant sample. Due to their relative heterogeneity, laboratory-type rooms were audited in particularly great numbers (approx. 20% of all labs were audited). The types of laboratories distinguished in the studies were:

- Laboratory animal quarters and service spaces in support of life and health science research
- Teaching laboratories in engineering and physical and life and health science departments
- Research offices in the engineering and physical and life and health science fields; nearly always within suites of research facilities.
- Research laboratories and laboratory service rooms in engineering and physical science fields
- Research laboratories and laboratory service rooms in life and health science fields

Note that hospitals were also included in the study. However, for the purposes of this report, hospital energy usage is treated above in the statewide assessment based on data from the California Energy Commission (see **Appendix A**).

Audit results were used to develop DOE-2 simulation models for each room type and the models were then used to develop total energy intensity and consumption estimates for each campus. The approach and results are described in detail in **Appendix C** and **Table C-1**.

There are approximately 13,000 rooms in which laboratory-type tasks are conducted in the five campuses. Laboratory-type facilities at the five campuses studied represent about 25% of total floor area in the UC Campuses (4 million square feet of laboratory-type space), out of a total area of 15.9 million square feet. However, due to their high energy intensities, they represent 56% and 58% of total electricity and gas use, respectively (**Table 7**).

Table 7. Summary Data on Laboratory and Non-Laboratory Energy Use at University of California Campuses.

FLOOR AREA	Total (ft^2)	Laboratory (ft^2)				
UCLA	5,732,862	1,316,412				
UCB	5,657,565	1,250,627				
UCSD	2,140,782	645,652				
UCI	1,180,455	344,323				
UCSF	1,165,746	460,617				
TOTAL	15,877,410	4,017,631				
		ELECTRICITY			NATURAL GAS	
TOTAL ENERGY USE	Total (MWh/yr)	Labs (MWh/yr)	Ratio (Lab/Total)	Total (MMBTU/yr)	Labs (MMBTU/yr)	Ratio (Lab/Total)
UCLA	248,034	137,958	56%	1,710,691	974,844	57%
UCB	135,714	69,976	52%	962,105	539,291	56%
UCSD	86,990	51,028	59%	520,676	324,229	62%
UCI	50,938	31,173	61%	297,360	202,915	68%
UCSF	37,998	25,586	67%	357,410	204,233	57%
TOTAL	559,674	315,722	56%	3,848,242	2,245,512	58%
ENERGY INTENSITIES	Non-Lab (kWh/ft^2-y)	Lab (kWh/ft^2-y)	Ratio (Lab/Total)	Non-Lab (100kBtu/ft^2-y)	Lab (100kBtu/ft^2-y)	Ratio (Lab/Total)
UCLA	25	105	4.2	1.67	7.41	4.44
UCB	15	56	3.8	0.96	4.31	4.49
UCSD	24	79	3.3	1.31	5.02	3.82
UCI	24	91	3.8	1.13	5.89	5.22
UCSF	18	56	3.2	2.17	4.43	2.04
TOTAL	21	79	3.8	1.35	5.59	4.14

Corresponding laboratory energy use was 316 GWh/year of electricity and 2.2 x 10^{12} BTU of natural gas. UCLA consumption is nearly twice that of the next-largest Campus.

Average energy intensities in laboratory-type facilities were ~80 kWh/ft^2-year for electricity and 5.6 therms/ft^2-year for natural gas.

Compared to the non-laboratory facilities (for which offices are used as a proxy) laboratories consume about four-times as much energy on a per-square-foot basis on average. The ratio varies from campus to campus and from fuel to fuel (**Figure 10**). Variations among specific types of laboratories are shown for the case of UCLA in **Figure 11**. Animal laboratories show the greatest relative energy intensity, followed by laboratories for life & health sciences and for engineering & physics. These estimates are likely to be less than those found in non-university facilities for the reasons discussed in Section 1 above.

Figure 10

Lab vs. Non-Lab Energy Intensities: 5 UC Campuses

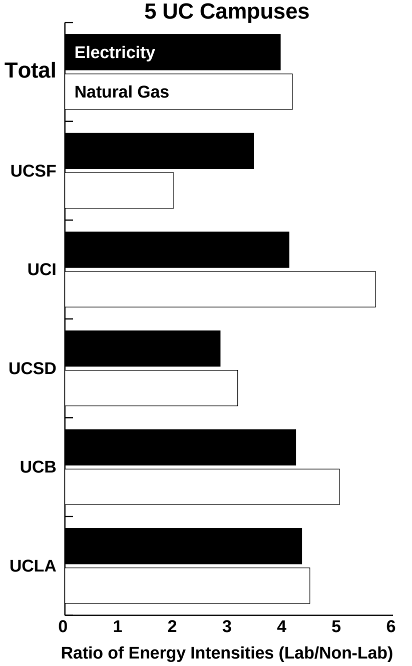
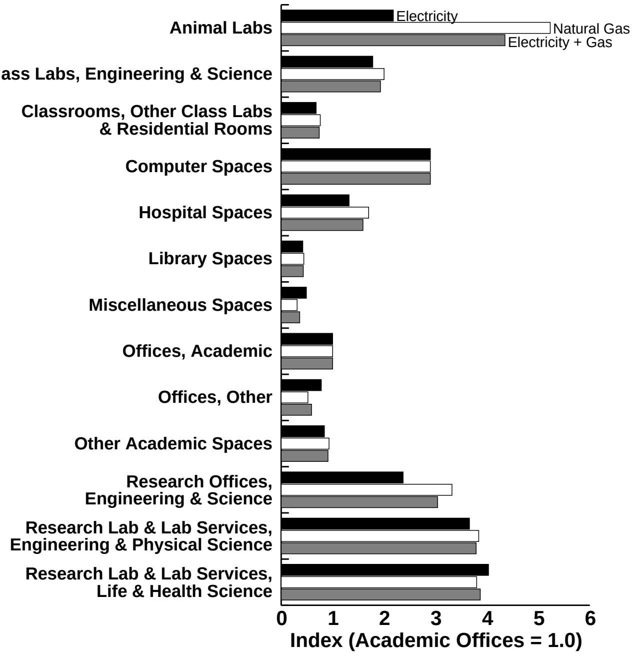


Figure 11

UCLA Building Energy Intensities Relative to Offices



The most energy-intensive categories of labs are in the range of 120-140 kWh/ft^2-year (electricity) and 10-15 therms/ft^2-year (natural gas). In the case of electricity, this upper range represents 6-7 times the electricity intensity and 7-10 times the natural-gas intensity of non-laboratory spaces at the Universities.

The results also allow for a comparison of offices located within laboratory complexes to ordinary office spaces. In most cases, these offices were two- to four-times as energy intensive as much ordinary offices.

National Laboratories

The U.S. Department of Energy's National Laboratories and other facilities represent major laboratory-type facilities in many parts of the country, and represent the full range of laboratory functions. Three sites located in California contain significant amounts of laboratory-type spaces. These are Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and The Stanford Linear Accelerator.

Floor area for laboratory-type facilities at LBNL and LLNL totals 1.9 million square feet, representing 33% and 38% of total floor area at the Labs, respectively. It was not possible to separate the laboratory-type from total floorspace at SLAC. Total floor area for the three sites is 2.6 million square feet.

Energy data for the National Laboratories is compiled by the Department of Energy, and is reported annually according to Federal Energy Management Program requirements. The total for the three sites is approximately 650 GWh of electricity and 700 billion BTUs of fuel, with approximately half used at LLNL, 40% at SLAC, and 10% at LBNL. Taken together, the energy use at these three sites represents 7% of statewide energy use in laboratory-type facilities.

The DOE In-house Energy Management (IHEM) Program was established in 1975 to implement energy-efficiency improvements at DOE sites across the United States.[9] These diverse sites comprise over 14,000 buildings and 120 million square feet of floor area. IHEM buildings-related programs include studies, retrofits, new construction, metering, and energy savings performance contracting. Between 1977 and 1994, $47 million was invested in studies and $290 million in 1100 retrofit projects, with an average payback time of 3 years. This corresponds to an annual savings level of $100 million and a return on investment in excess of 25%. DOE has cost-effectively reduced its energy consumption in buildings by 43% since 1975, surpassing the fiscal year 2000 requirement of the Energy Policy Act of 1992.

The IHEM program's annual reports document energy savings resulting from a variety of retrofit measures at DOE facilities across the country, including a host of laboratory-type facilities. These reports describe retrofit projects targeted at buildings-related end uses as well as process-related end uses.[10] The DOE/IHEM program is perhaps the most comprehensive energy management program for laboratory-type facilities in the country.

V. The Design of Energy-Efficient Laboratory-Type Facilities

Overview of Design Principles

Research laboratories are sophisticated and complex environments that are designed to meet the demands of research tasks, while providing safe environments for workers. This double mission means that laboratories must exceed the levels of safety, comfort, and indoor air quality maintained in conventional office buildings. To this end, designs of research laboratories have been typically completed with minimal regard for energy use.

A research laboratory environmental conditioning system must also provide protection and comfort for occupants of the laboratory building, including those in non-research spaces. The integration of dissimilar types of spaces increases the potential for energy waste.

Numerous texts and guides deal with design and engineering of laboratory facilities. However, little information is available on energy-efficient design.

The energy-efficiency design process is an iterative one that begins by establishing communication among all members of the design team. Each design discipline has an impact on the energy load; on a macro scale, the flexibility of the architectural design permits or presents such measures as a large efficient conditioning system. On a micro scale, the choice of a lighting system can affect sensible heat gain and transformer sizing, for example. Energy-efficient design solutions in laboratories determine the potential variability of a minimized load and matches the load with flexible, adjustable electrical and mechanical conditioning system(s). The process can be outlined as follows:

- **Identify Potential Variability**

Laboratory facilities are very energy intensive, primarily because of the large volumes of conditioned air necessary for safety and process ventilation. Therefore, the energy engineer must determine the potential variation of energy loads on hourly, daily, annual, and life-cycle bases. Recognition of load diversity is a key factor in energy-efficient laboratory design. Each laboratory facility will be operated in a unique manner commonly referred to as the "Profile of Use," that may or may not vary during a given time frame. For example, some highly specialized research requires a 24-hour-a-day commitment. When this kind of research is located in a mild climate, the variability of the environmental conditioning load is likely to be small. By contrast, operation of a laboratory in a university environment may be extremely variable because of odd-hour use, class sizes, and semester cycles (even in a mild climate).

- **Minimize the Load**

While variability of energy load is being identified, the design team must simultaneously focus on minimizing potential energy load. Research laboratories have been compared to wind tunnels because of the large volumes of air moved through them, typically ten times greater than in an office building. Minimizing this air volume substantially reduces energy consumption; however, because of the volume of air flow, a traditional energy saving measure like wall and roof insulation will not have a big effect on energy efficiency. The main air-volume energy loads that need to be minimized are provided by an environmental conditioning system:[11]

- thermal (sensible), e.g., heating and cooling;
- latent, e.g., humidification or de-humidification;
- air movement, e.g., fans and motors/drives;
- circulation, e.g., pumps and motors/drives; and
- miscellaneous support and peripheral equipment.

The energy engineer should first *qualify* and then *quantify* the load as follows:

- qualify the load with researchers and owner(s) to: inform them of the energy-use implications of all choices they make regarding lab environmental conditions, determine the range of acceptable lab environment conditions, specify the tolerance to which the lab environment must be held, and try to enlarge the “comfort envelope” by explaining the energy consumed to maintain restrictive temperature and humidity conditions. For instance, an excessively tight relative humidity (R.H.) range consumes a large amount of energy and may require cooling and reheating coils in the air supply system.

- quantify the load by: complying with the code requirements; providing certification when necessary, as in the case of biological safety cabinets; maintaining required researcher/user safety and environmental conditions; employing computer-based simulation tools to analyze life-cycle cost benefits of alternative, competing designs. Rule-of-thumb calculations should be questioned; thoroughly consider climate and user operation in all load calculations.

- **Match Variable Load with an Adjustable System**

A flexible, adjustable environmental system should be designed in concert with all of the design, so that the system can match load variations to achieve maximum energy efficiency. A flexible, adjustable system adapts by means of staged operation of modules and devices that can be modulated to satisfy the current load. Engineers must consider the part-load efficiency of an environmental conditioning system.

- **Use an Integrated Energy Engineering Approach**

The Integrated Energy Engineering or “Right Sizing” approach to laboratory facility design considers interdisciplinary and interactive energy relationships among: architecture, facility programming and planning, electrical and mechanical engineering, economics, industrial safety, and facility operation and maintenance. Energy engineers should promote and share design ideas aimed toward minimizing a facility’s total energy use, not just the energy consumed by its environmental conditioning system. The interrelationship of an electrical system design provides a good example of this interactive design methodology. When closely analyzed, an energy efficient lamp reduces the waste heat within a facility which, in turn, means a smaller HVAC system is needed. A smaller HVAC system permits a reduced transformer size and a smaller emergency generator.

- **Understand Barriers**

The goal of the energy-efficient design process is to consider all energy efficiency options and incorporate the best into the design. However, numerous real and perceived barriers exist, such as higher than normal first-costs, and out-of-date design standards. Creating an energy-efficient laboratory design requires an understanding of and willingness to surmount these barriers; with persistence, an energy engineer can optimize system performance and individual components to produce an effective, integrated, energy-efficient design.

Barriers to Energy-Efficiency in Laboratory-Type Facilities

A comprehensive list of barriers to energy efficiency design improvements follows, compiled at a workshop that focused on cleanroom design. The list also applies to other research laboratory facilities and include:[12]

- Standard design practices are based on old technologies or inaccurate assumptions. Outdated assumptions include: sizing airside pressure drops for a fixed static pressure; sizing water systems for a fixed amount of head; using high coil and filter face velocities.

- Considerable emphasis is placed on system first-cost although lower first-cost may result in higher life-cycle costs. Design teams need to consider life-cycle costs, which often justify higher-first-cost, energy-efficient equipment.

- Time and priority need to be given to working out new, nontraditional designs. Energy-efficient designs may require additional staff time or consultants.

- The conservative facility building culture often resists new ideas. Innovators carry a heavy burden to prove the efficacy of their new designs; in addition, designers may risk legal consequences if the laboratory’s operation does not meet design specifications/design basis documents.

- Benchmarking of energy costs is lacking. If an existing facility does not already track what it costs to operate each component, management has little information on which to base decisions about possible improvements in energy use.

- Size limitations for code requirements may adversely affect environmental conditioning system designs. For example, limiting the height of the penthouse where the air-handlers are located may prevent optimal configurations of systems.

- Inadequate space may be available for energy-efficient equipment. Currently, the architect often designs the facility and then tells the engineers how much space they have. Early cooperation between the design team members is necessary to devise optimum configurations.

- Performance envelope specifications may limit possibilities for energy efficiency. When the performance envelope, i.e. operating range of the facility, can be expanded—for example, increasing the allowable relative humidity—lower first-costs and operational energy costs may result. Owners and occupants need to clearly understand the impacts of design tolerances on facility energy performance.

- Designers who are familiar with energy-efficiency concerns in laboratory-type facilities are in short supply.

Advanced Design Strategies

Current cutting-edge solutions include right-sizing techniques, diversity appraisal, DDC systems, VAV systems, modular boiler plants, turn-down ratios for chillers, minienvironments, indirect-direct evaporative cooling, and heat recovery. A comprehensive design process combines measures to create a smoothly operating facility with low life-cycle costs. *The Design Guide for Energy-Efficient Research Laboratories* that accompanies this report provides extensive detail on each of the following strategies.

- **Integrated System Design: Right-Sizing for Energy Efficiency**

The techniques of right-sizing integrate the many interactive relationships that influence the capacity of the environmental conditioning system. The goal of right-sizing is to prevent over-design of the space-conditioning system; excessive capacity in a large system wastes energy and increases first-costs. The engineering team must determine whether the facility's design conditions are overstated; typically, the specified comfort envelope can be enlarged, reducing the required conditioning system capacity Another right-sizing technique is appraisal of conditioning system diversity, which is based on the assumption that all laboratory equipment is unlikely to operate simultaneously; a diversity analysis determines the average system capacity that will accommodate part-load operation. A variable air volume (VAV) system can efficiently accommodate part-load operation.

- **Energy Monitoring and Control System with Direct Digital Control**

An energy monitoring and control system (EMCS) that incorporates direct digital control (DDC) is an absolute necessity in certain situations. If properly designed, installed, and maintained the EMCS insures energy-efficient operation of the facility by monitoring, controlling, and tracking energy consumption. Traditionally, EMCS's have been provided to facilities by manufacturers with little input from design team engineers. It is strongly recommended that energy engineers take a more proactive role in EMCS selection from the design of the sequence of operations to the specification of the kinds of sensors and operators to be installed.

- **Variable Frequency Drives (VFD) and Air Flow Rates**

Air handling equipment is typically sized so that it operates at only 70 percent of its full-load rating. Incorporating a variable frequency drive (VFD) that uses duct static pressure as a control input can pay for itself in less than two years. The VFD's lower air velocity reduces pressure loss and increases operating efficiency of a heat recovery device if one is present; these improvements more than compensate for higher system first-costs. When the laboratory is unoccupied, the rate could be reduced to 50% of the nominal value, decreasing the energy consumption of the entire air handling system to less than 25% of that required for a conventional system.

- **Modularized Plant Devices**

Conditioning equipment can be designed in modules that can operate singly or together to meet part or full loads. Modules include multiple boilers and chillers that can have their operation staged to meet the load. Devices whose operation can be modulated include: variable air volume (VAV) supply and fume hood exhaust systems and variable frequency drives (VFDs) on fans and pumps. EMCS's can modulate heating and cooling temperatures with real-time precision. All of these modules and devices take advantage of the facility's diversity and maximize system part-load efficiency.

- **Segregating Tasks with Mini-Environments**

Laboratory temperature and humidity design conditions are typically specified to satisfy both process and human comfort needs. Segregating critical areas with narrow environmental tolerances from other non-critical areas saves energy. One method is to subdivide systems and zones into mini-environments.

- **Indirect-Direct Evaporative Cooling**

The higher the allowable humidity, the greater the energy savings. As the allowable humidity range increases, the use of energy-efficient indirect-direct evaporative cooling becomes more appropriate. According to one study, when the laboratory relative humidity range is 45 - 50 percent, evaporative cooling can be used consuming only two-thirds of the energy required to provide a range of 40 – 45 percent R.H., which requires use of a chiller. Laboratories in warmer climates benefit from raising the allowable R.H.; laboratories in colder climates benefit most from lower minimum R.H. specifications as well as a wider range.[13]

- **Other Measures**

Numerous other measures can be employed in an energy-efficient laboratory conditioning system:

- recover heat from the exhaust air or process cooling water with run-around coils; recover both sensible and latent energy with heat wheels
- incorporate low-face-velocity coils and filters
- choose the lowest pressure drop filter for the efficiency required
- utilize free cooling with a plate-and-frame heat exchanger instead of the chiller and oversized cooling towers
- minimize energy-intensive air cooling and humidification by using evaporative cooling
- use premium efficiency equipment when selecting motors, lamps, boilers, chillers, fans, etc.
- use variable outside air for support spaces that have economizers
- reuse air from office/support spaces to reduce the need for the mechanical cooling in the laboratories
- use chiller waste heat for heating purposes.

Integrated Energy Design: The Example of Cleanrooms

Cleanrooms offer an excellent opportunity to illustrate the value of taking an integrated design approach. Energy-using systems within cleanrooms (HVAC, lighting, and plug loads) interact tightly. Many efficiency gains can only be acquired through a comprehensive approach. The non-energy benefits of energy-efficiency options are also well-illustrated in the case of cleanrooms, i.e. improvements to the process being conducted. **Appendix B** presents detailed examples of options for cleanrooms, and the energy savings that can result.

VI. A Design Guide for Energy-Efficient Research Laboratories

Based on the philosophy elaborated above, we have developed *A Design Guide for Energy-Efficient Research Laboratories* to encourage design teams to develop expertise in energy-efficient laboratory design.[14] The Design Guide team had an opportunity to test preliminary concepts by participating in a value-engineering process for a new laboratory building being designed for UC Irvine.

The Guide provides a detailed and holistic framework to assist designers and energy managers in identifying and applying advanced energy-efficiency features in laboratory-type environments. The Guide fills an important void in the general literature and compliments existing in-depth technical manuals. Considerable information is available pertaining to overall laboratory design issues, but no single document focuses comprehensively on energy issues in these highly specialized environments. Furthermore, practitioners utilize many antiquated rules of thumb, which often inadvertently foster energy inefficiency. The Guide help the user introduce energy decision-making into the earliest phases of the design process and facilitates access to the literature of pertinent issues and awareness of debates and issues on topics. The Guide focuses on individual technologies, as well as control systems, and important operational factors such as building commissioning. Most importantly, the Guide is designed to foster a systems perspective (e.g. “right sizing”) and to present current leading-edge design practices and principles.

Energy-efficient laboratories offer the research community cost savings and safer working conditions in addition to serving the larger social good of reducing energy consumption. The laboratory designer with expertise in energy-efficient design will remain competitive in a world that increasingly values energy savings (and the resulting cost savings). Although the recommendations in the Guide may seem new, they are proven, and the field of energy efficiency continues to move ahead. The Guide does not provide calculation methods to determine energy savings of a design. However, references to in-depth calculation procedures are given.

The chapters consider all phases of the design process that influence a laboratory facility’s energy consumption. Including design solutions that directly or indirectly affect energy use. An example of a solution with direct impact is specification of fume hood face velocity; the amount of exhausted conditioned air is proportional to this value. A solution with an indirect impact is selection of throw velocity of the supply diffuser near a fume hood; this choice influences the performance of an energy-efficient fume hood with a lower than normal velocity. An assumption that would adversely affect energy efficiency (and safety) is that a high value (greater than 125 fpm) for the face velocity increases the operator’s safety, without considering the throw velocity of a supply diffuser near the fume hood.

Guide compiles information from an extensive literature search of approximately 150 research papers, conference proceedings, design texts, case and other studies, recommended practice, and manufacturers’ experience. Additional information was gathered from the practicing engineering community; from energy systems specialists; including scientists and in-house energy managers at Lawrence Berkeley National Laboratory.

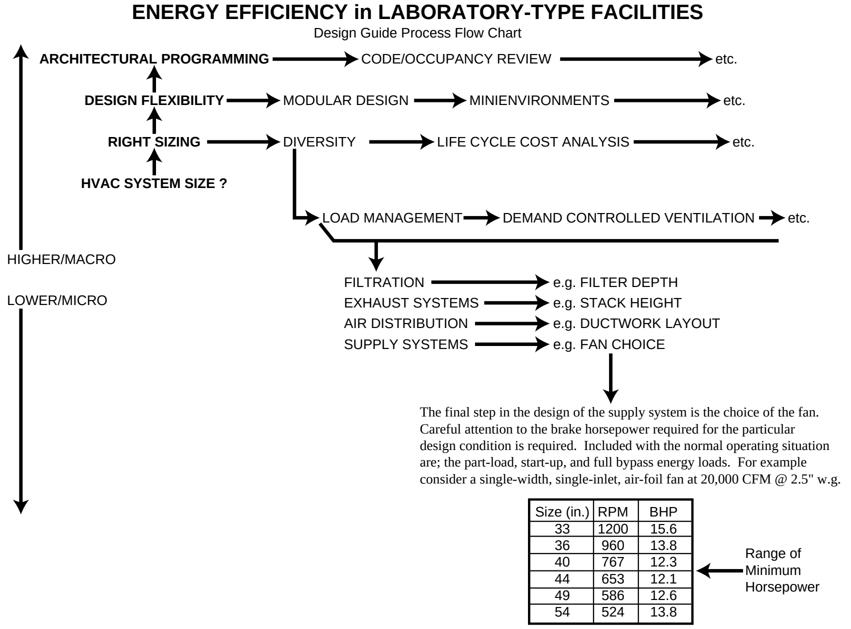
The guide is designed to address multiple audiences: building owners, researchers, planners, architects, engineers, and designers. The guide provides information at four increasingly technical levels. The guide is not meant to be a resource for all design elements of a laboratory facility, but rather to complement existing publications by focusing on information on energy efficiency only. The chapters consider the energy-efficiency aspects of the following areas (See **Appendix D** for more detailed listing of topics covered):

- Architectural Programming
- Integrated System Design: Right-Sizing for Energy Efficiency
- Digital Control Systems
- Supply Systems
- Exhaust Systems
- Distribution Systems
- Filtration Systems
- Lighting Systems
- Commissioning

This Guide is intended for research laboratory-type facilities, such as those found in universities, and for commercial and industrial research facilities, including laboratories and cleanrooms. These facilities typically have Uniform Building Code (UBC) occupancy classifications of B-2, H-8, or H-7. When we use the word “cleanroom,” we mean research and not production scale facilities.

This Guide is arranged in a hierarchical format from moving the macro to the micro (**Figure 12**). The broadest issues, a building’s architectural configuration and its UBC code classification, are reviewed first, in the expectation that the input of an energy efficiency expert can influence the overall design configuration and possibly classification of a building. The micro issues are quite specific—the impact of air filtration on energy efficiency, for example. The selection of an air filter has a large influence on energy use, particularly in high-air-quality laboratories.

Figure 12: Conceptual approach to Laboratory-Type Facility Design, Illustrating the Case of Fan Choice



The final step in the design of the supply system is the choice of the fan. Careful attention to the brake horsepower required for the particular design condition is required. Included with the normal operating situation are; the part-load, start-up, and full bypass energy loads. For example consider a single-width, single-inlet, air-foil fan at 20,000 CFM @ 2.5" w.g.

Size (in.)	RPM	BHP
33	1200	15.6
36	960	13.8
40	767	12.3
44	653	12.1
49	586	12.6
54	524	13.8

VII. Research Agenda

The following is a brief synopsis of fertile research topics, offering the prospect of new ways to secure energy savings in laboratory-type facilities while simultaneously offering measurable improvements in the quality and non-energy performance of those facilities.

We identify five major avenues of research that would serve to improve energy efficiency in laboratory-type facilities:

1. Technology R&D
2. Technology Transfer
3. Additional Design Guides
4. Design Guide Validation
5. Field Assessment of Additional Opportunities

Our market and energy use assessments support this agenda:

- Our review of the existing energy data revealed a paucity of sources of information (e.g. end-use profiles, load-shape analysis) that is fundamental to understanding the deeper patterns of energy use in laboratory-type facilities. We have identified no thorough simulation studies of laboratory-type facilities, nor have we been able to identify laboratory-specific energy estimates (end use or total) within the California energy utilities. One current obstacle is the deficiency of clear protocols, survey strategies, and tools for the necessary monitoring and data collection.

- Our review of current design practice, and the very processes of design, reveal pervasive and deeply ingrained design practices that fail to capture the potential for energy efficiency in laboratory-type facilities.

- There is a considerable gap between current best-practice in laboratory design and typical practice. The lack of comprehensive information (in the form of electronic tools or paper-based media) calls for improved transfer of state-of-the-art information to the mainstream practitioners. The increased use of networked information systems, including wide-area networks such as the Internet offer an excellent vehicle for technology and information transfer.

Certain technology R&D avenues also emerge from our analysis:

- Cleanrooms emerge from our analysis as the number-one energy-using laboratory facility type in California. They represent approximately 55% of the total laboratory energy use in the State and are found in a wide variety of applications (over 30 SIC code categories). The efficiency potential here is immense, but current practice falls far short of the goal. The problem concerns both individual technologies and components and the lack of an integrated design optimization approach. The outlook for 4% per year growth in cleanroom floor area suggests another reason for emphasis on this particular type of laboratory building.

- Ventilation in cleanrooms and other types of laboratory facilities is a key issue, and the currently used devices (e.g. fume hoods) are not optimized in terms of either component efficiency or application efficiency.

- In other sectors, (e.g. conventional office buildings) energy design tools have proved invaluable in the process of saving energy. For the laboratory segment, there are no comprehensive tools and thus this should be an area of focus for future efforts. Given the complexity and number of players, tools enabling the documentation of design intent would likely prove quite valuable.

We group the specific recommended research activities into three key (and complementary) areas:

1. Design Processes and Energy Data Diagnostics
2. Technology and Systems Integration
3. Indoor Environmental Management and Control Strategies.

Design Processes and Energy Data Diagnostics

- Design Guide & Design Process

The Design Guide currently being developed could be improved by conducting an application of the tool to one or more laboratory efficiency projects. This would no doubt yield further evaluations of existing rules of thumb and better guidance on right-sizing. A modified version (or modules) could be prepared to cover production (vs. research) type facilities. A free-standing, hyper-text electronic version or optional linkages to other tools (such as Buildings Design Advisor, PowerDOE, or the Building Lifecycle Information Support System) would greatly increase the chances for the tool's use by practitioners. Convenient spreadsheet-like calculation modules and tables could be built right into an electronic guide. An electronic version could be tailored so as to generate attachments to construction documents, documentation of design intent, etc. Further efforts should be made to relate and link the tool to pre-existing design and decision-making processes. Mounting the tool on the World Wide Web would also address this issue, e.g. by allowing multiple users at different sites to use a common version of the tool, and download current project information.

- Parametric Studies

While large numbers of parametric simulation studies have been performed to identify the impacts of energy-efficiency options for ordinary commercial buildings, little such work has been done for laboratory-type facilities. A series of prototype laboratories (e.g. cleanrooms, animal labs, biotech labs) should be developed and used to evaluate key energy-efficiency measures in several representative climates. This exercise could be coupled with the Design Guide and used throughout the Guide to illustrate the prospective impacts of the technologies and strategies discussed therein. One topic that merits investigation is the energy use by "ordinary" spaces adjoining laboratory-type spaces. As evidenced by the in-depth evaluation of energy use in University of California facilities, such spaces are consuming 2- to 4-times as much energy as ordinary offices.

- End-Use Monitoring and Diagnostics

Toolkits being developed under CIEE's project with UCB/CEDR could be applied to a variety of laboratory-type buildings in the State.[15] Adding more buildings with strategic relevance to the larger Program interests; Seeking cleanroom (or other hi-tech) partners to join CIEE Diagnostics Project; and applying data visualization and operator-feedback strategies to laboratory-type environments are all likely to be fertile areas for further investigation.

Technology and Systems Integration

- Airflow Design Criteria to Minimize Fan Power Consumption

Utilization of a comprehensive systems perspective to articulate generalized technical criteria on duct and plenum airspeeds, minimum turning radii, transition criteria, turning vane criteria, coil air-resistance parameters, VAV resistive losses, and pressure losses for louvers and other termination devices in the HVAC chain. This is one of many potential areas for deepening the content of the Design Guide, or for a free-standing analysis.

- Cleanroom Systems Optimization

  We propose a comprehensive "Cleanroom of the Future" project, implementing a lifecycle approach, in partnership with a cleanroom design, construction, and energy management firm, one or more utilities, and cleanroom component manufacturers. The project would address fundamental issues of cleanroom space-conditioning systems, layout, minienvironments and robotics, as well as optimizing individual component technologies, (e.g., fans), sensors, filtration, and control systems. The project would also address reduction of process loads (e.g. use of notebook computers), which can generate multiple non-energy benefits that enhance the quality and performance of the cleanroom work environment.

- Lighting Alternatives for Cleanrooms and Explosion-Hazard Settings

  Both light guides and fiber-optic systems, coupled with ultra-efficient light sources, offer promise. Light guides have a certain appeal, but low overall system optical efficiencies are a barrier for current technologies. Non-energy benefits include reduced EMI/RFI, less vulnerability to aggressive cleaning chemicals, avoidance of ballast outgasing and carbon shedding by ordinary fluorescent pinholders, reduced interference with room air flow, ability to change spectral distribution of light output, reduction of crevices/gaps that harbor bacteria/virus/particles/gases, acoustical control, and possible integration with other services e.g. loudspeakers.

- Innovative Fume Hood Designs

  High face velocities are currently used to try to maintain stability in the containment zone of fume hoods. The associated high airflow rates are very energy-intensive. Investigation of innovative strategies for creating increased stability in the containment zone could lead to improved containment and cost savings.

- Plug and Process Loads; Load-Shape Analysis

  Plug and process loads play a critical role in overall laboratory energy use and in system sizing. None of the major California utilities contacted at the outset of this study report having any significant knowledge of these loads or the pertinent efficiency options.

Indoor Environmental Management and Control Strategies

- Strategies for Minimizing Pressure Drop

  The reduction of pressure drop in laboratory facilities can be advanced by a combination of several technology developments, including (a) development of sub-micron high-efficiency particulate air filters, with substantially reduced pressure drop, and (b) development of a software package (or of a module that can be integrated with existing tools) for optimal design of cleanrooms and other environments, to minimize the required energy for air recirculation and make-up with an optimized arrangement of conditioned systems and components including the application of minienvironments and robotics. New simulation packages (or modules) would take into account the most current design arrangements of proven energy-efficient laboratory-type facilities.

- Control of Air Flow Rate with Sensor-Based Demand-Controlled Ventilation

  In many lab-type industries there are significant fluctuations in the usage and production rate with a corresponding fluctuation in the pollutants generated by the laboratory activities. It has been suggested that if laboratory ventilation rates can be adjusted as a function of the process requirements, measured by suitable sensors, very substantial savings could be achieved.[16] However, formidable barriers to this strategy are posed the potential for such measures to complicate management of critical processes in the laboratory/production environment.

The SBDCV application potential, technical merit, non-energy impacts, and practicality may be assessed by the following targeted R&D activities (some of which may already have or can be expected to find adequate R&D support from the private sector):

- Inexpensive, robust, sensitive, selective, accurate and stable real-time sensors which can measure pollutants found in the indoor industrial environment.

- Low cost and reliable particle counters for smaller size particles, and chemical classification and counting by type (“speciation”) of particles.

- Low-pressure-drop, high efficiency and long-life active air cleaners that can be used to remove pollutants from industrial indoor air and from outside air.

- Improved computer based HVAC monitoring and control systems taking advantage of the inputs of different sensor types (such us particles, VOCs, CO_2, CO, humidity, temperature), improved human-machine interface, response algorithms for real-time pricing, production cost and quality factors.

- The influence of the number and the location of sensors in different industrial building configurations.

Endnotes

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APPENDIX A. Energy Use in CA Laboratory-Type Facilities [1].

				Contains Labs		*Predominantly Labs*	
SIC	Code Description	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)
2700	Printing & Publishing	7.0	0.1				
2710	Newspapers	33.8	0.0				
2711	Newspapers	342.7	4.1				
2720	Periodicals	2.5	0.0				
2721	Periodicals	34.8	0.3				
2730	Books	2.6	0.0				
2731	Book Publishing	31.7	0.4				
2732	Book Printing	6.6	0.1				
2740	Miscellaneous Publishing	3.5	0.0				
2741	Miscellaneous Publishing	43.8	0.2				
2750	Commercial Printing	44.5	0.0	44.5	0.0		
2751	Commercial Printing Letter Press (2759)	6.1	0.0	6.1	0.0		
2752	Commercial Printing, Lithographic	447.1	14.3	447.1	14.3		
2753	Engraving and Plate Printing (2796)	0.7	0.0	0.7	0.0		
2754	Commercial Printing, Gravure	2.0	0.0	2.0	0.0		
2759	Commercial Printing, nec	91.7	2.0	91.7	2.0		
2760	Manifold Business Forms	0.7	0.0				
2761	Manifold Business Forms	38.5	0.5				
2770	Greeting Cards	0.0	0.0				
2771	Greeting Cards	0.9	0.0				
2780	Blankbooks & Bookbinding	1.0	0.0				
2782	Blankbooks & Loosleaf binders	15.0	0.1				
2789	Blankbooks & related	56.7	1.2				
2790	Printing Trade Services	1.3	0.0				
2791	Typesetting	9.4	0.0				
2793	Photoengraving (2796)	0.1	0.0				
2794	Electrotyping and Stereotyping (2796)	0.4	0.0				
2795	Lithographic Platemaking (2796)	4.6	0.0				
2796	Platemaking Services	15.5	0.1				
2800	Chemicals & Allied Products	17.9	0.0	17.9	0.0		
2810	Industrial Inorganic Chemicals	129.7	0.0	129.7	0.0		
2812	Alkalies & Chlorine	18.7	3.2				
2813	Industrial Gases	940.9	31.7				
2816	Inorganic Pigments	40.3	1.2				
2819	Industrial Inorganic Chemicals	1182.9	78.6				
2820	Plastics Materials & Synthetics	14.4	0.0				
2821	Plastics Materials & Resins	173.6	12.2				
2822	Synthetic Rubber	12.5	0.2				
2823	Cellulosic Manmade Fibers	0.3	0.0				
2824	Organic Fibers, Noncellulosic	3.3	0.1				
2830	Drugs	27.2	0.4	27.2	0.4	27.2	0.4
2831	Biological Service (2835, 2836)	0.0	0.2	0.0	0.2	0.0	0.2
2833	Medicinals & Botanicals	40.5	31.0	40.5	31.0	40.5	31.0
2834	Pharmeceutical Preparations	340.1	14.7	340.1	14.7	340.1	14.7

				Contains Labs		*Predominantly Labs*	
SIC	Code Description	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)
2835	Diagnostic Substances	14.7	0.4	14.7	0.4	14.7	0.4
2836	Biological Products	37.2	2.8	37.2	2.8	37.2	2.8
2840	Soap, Cleaners, & Toilet Goods	13.2	0.0				
2841	Soap & Detergents	81.3	36.3				
2842	Polishes & Sanitation Goods	18.0	0.9				
2843	Surface Active Agents	4.7	0.7				
2844	Toilet Preparations	54.3	1.4				
2850	Paints & Allied Products	1.7	0.0				
2851	Paints & Allied Products	59.1	1.1				
2860	Industrial Organic Chemicals	0.2	0.0				
2861	Gum & Wood Chemicals	3.6	0.2				
2865	Cyclic Crudes & Intermediates	14.7	0.1				
2869	Industrial Organic Chemicals	41.9	3.0				
2870	Agricultural Chemicals	1.7	0.2				
2873	Nitrogenous Fertilizers	38.5	2.7				
2874	Phosphatic Fertilizers	1.1	0.0				
2875	Fertilizers, Mixing Only	1.3	0.1				
2879	Agricultural Chemicals	32.5	10.3				
2890	Miscellaneous Chemical Products	9.3	0.0				
2891	Adhesives & Sealants	31.9	3.5				
2892	Explosives	10.0	0.1	10.0	0.1	10.0	0.1
2893	Printing Ink	18.5	0.5				
2895	Carbon Black	0.1	0.0				
2899	Chemical Preparations	171.0	13.6				
3570	Computer & Office Equipment	1052.2	14.6	1052.2	14.6	1052.2	14.6
3571	Electronic Computers	290.0	2.7	290.0	2.7	290.0	2.7
3572	Computer Storage Devices	121.2	0.5	121.2	0.5	121.2	0.5
3573	Electronic Computing Equipment (3571, etc)	33.9	0.0	33.9	0.0	33.9	0.0
3575	Computer Terminals	15.2	0.3	15.2	0.3	15.2	0.3
3577	Computer Peripherals	115.0	0.2	115.0	0.2	115.0	0.2
3578	Calculating & Accounting Equipment	16.6	0.0	16.6	0.0	16.6	0.0
3579	Office Machines	10.9	0.1	10.9	0.1	10.9	0.1
3500	Industrial Machinery & Equipment	0.6	0.1				
3510	Engines & Turbines	0.7	0.0				
3511	Turbines & Turbine Generators	17.1	2.1				
3519	Internal Combustion Engines	5.2	0.0				
3520	Farm & Garden Machinery	0.1	0.0				
3523	Farm Machinery & Equipment	27.9	0.9				
3524	Lawn & Garden Equipment	2.1	0.1				
3530	Construction & Related Machinery	2.7	0.0				
3531	Construction Machinery	21.4	1.0				
3532	Mining Machinery	1.6	0.1				
3533	Oil & Gas Field Machinery	12.5	0.1				
3534	Elevators & Moving Stairway	3.1	0.0				

				Contains Labs		*Predominantly Labs*	
SIC	Code Description	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)
3535	Conveyors & Conveying Equipment	4.0	0.1				
3536	Hoists, Cranes & Monorails	2.0	0.0				
3537	Industrial Trucks & Tractors	8.9	0.2				
3540	Metalworking Machinery	11.5	0.0				
3541	Machine Tools, Metal Cutting Types	66.7	0.3				
3542	Machine Tools, Metal Forming Types	17.9	0.3				
3543	Industrial Patterns	1.7	0.1				
3544	Special Dies, Tools, Jigs	69.1	0.9				
3545	Machine tool Accessories	28.0	0.4				
3546	Power Driven hand Tools	9.0	0.1				
3547	Rolling Drill Machinery	2.9	0.2				
3548	Welding Apparatus	3.5	0.0				
3549	Metal Working Machinery	7.5	0.4				
3550	Special Industry Machinery	6.5	0.1				
3551	Food Product Machinery (3556)	0.5	0.0				
3552	Textile Machinery	2.4	0.6				
3553	Woodworking Machinery	1.8	0.0				
3554	Paper Industry Machinery	1.2	1.4				
3555	Printing trades Machinery	11.2	0.8				
3556	Food Products machinery	12.1	0.7				
3559	Special Industry Machinery	50.1	0.9				
3560	General Industry Machinery	4.5	0.0				
3561	Pumps & Pumping Equipment	49.8	0.6				
3562	Ball & Roller Bearings	11.9	0.1				
3563	Air & Gas compressors	25.8	2.9				
3564	Blowers & Fans	7.6	0.1				
3565	Packaging Machinery	6.1	0.1				
3566	Speed Changers, Drives, Gears	10.4	0.3				
3567	Industrial Furnaces & Ovens	7.5	0.2				
3568	Power transmission Equipment	3.1	0.0				
3569	General Industrial Machinery	41.4	0.4				
3576	Scales and Balances (3596)	0.3	0.0				
3580	Refrigeration & Service Machinery	1.9	0.0				
3581	Automatic Vending Machines	8.3	0.5				
3582	Commercial Laundry Machines	0.2	0.1				
3585	Refrigeration & Heating Equipment	26.1	0.6				
3586	Measuring & Dispensing Pumps	0.3	0.0				
3589	Service Industry Machinery, nec	29.9	0.8				
3590	Industrial Machinery	21.8	0.0				
3592	Carburetors, Pistons, Rings, Valves	14.3	0.3				
3593	Fluid Power Cylinders & Actuators	2.2	0.0				
3594	Fluid Power Pumps & Motors	10.5	0.0				
3596	Scales & Balances	4.9	0.1				
3599	Industrial Machinery, nec	254.8	4.5				

				Contains Labs		*Predominantly Labs*	
SIC	Code Description	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)
3660	Communication Equipment	36.8	0.0	36.8	0.0		
3661	Telephone & Telegraph Apparatus	114.8	2.8	114.8	2.8		
3662	Radio and Television Equip. (3661, 3663)	3.2	0.2	3.2	0.2		
3663	Radio & TV Communications Equipment	216.4	2.3	216.4	2.3		
3669	Communications Equipment, nec	25.9	0.2	25.9	0.2		
3670	Electronic Components & Accessories	870.1	0.0	870.1	0.0	870.1	0.0
3671	Electron Tubes	145.7	3.4	145.7	3.4	145.7	3.4
3672	Printed Circuit Boards	251.6	1.2	251.6	1.2	251.6	1.2
3674	Semiconductors & Related Devices	1245.3	18.9	1245.3	18.9	1245.3	18.9
3675	Electronic Capacitors	15.5	1.6	15.5	1.6		
3676	Electronic Resistors	3.3	0.0	3.3	0.0		
3677	Electronic Coils & Transformers	30.5	0.1	30.5	0.1		
3678	Electronic Connectors	55.8	0.4	55.8	0.4		
3679	Electronic Components, nec	369.7	10.9	369.7	10.9		
3600	Electronic & Electric Equipment	6.2	0.0	6.2	0.0		
3610	Electric Distribution Equipment	3.6	0.0				
3612	Trasformers, Except Electric	20.1	0.4				
3613	Switchgear & Switchboard Apparatus	21.7	0.3				
3620	Electrical & Industrial Apparatus	4.7	0.0				
3621	Motors & Generators	36.4	0.3	36.4	0.3		
3622	Industrial Controls (3625)	0.4	0.0				
3624	Carbon & Graphite Products	15.3	0.0				
3625	Relays & Industrial Controls	36.8	0.2	36.8	0.2		
3629	Electrical Industrial Apparatus	7.9	0.2	7.9	0.2		
3630	Household Appliances	0.8	0.0				
3631	Household Cooking Equipment	3.4	0.1				
3632	Household Refridgerators & Freezers	4.3	0.0				
3633	Household Laundry Equipment	0.1	0.1				
3634	Electric Housewares & Fams	8.4	0.1				
3635	Household Vacuum Cleaners	0.1	0.0				
3636	Sewing Machines (3696)	0.0	0.0				
3639	Household Appliances	0.7	0.1				
3640	Electric Lighting & Wiring Equipment	9.2	0.0				
3641	Electric Lamps	6.7	0.3				
3643	Current-carrying Wiring Devices	54.1	0.5				
3644	Noncurrent-carrying Wiring Devices	22.3	0.9				
3645	Residential Lighting Fixtures	26.1	0.7				
3646	Commercial Lighting Fixtures	12.6	0.5				
3647	Vehicular Lighting Equipment	2.3	0.0				
3648	Lighting Equipment, nec	11.6	0.1				
3650	Household Audio & Video Equipment	36.5	0.0				
3651	Household Audio & Video Equipment	131.6	4.8				
3652	Prerecorded Records & Tapes	75.3	0.4				
3690	Misc. Electrical Equipment & Supplies	7.9	0.0	7.9	0.0		

				Contains Labs		*Predominantly Labs*	
SIC	Code Description	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)
3691	Storage Batteries	63.3	1.0				
3692	Primary Batteries, Dry & Wet	75.1	0.6				
3694	Engine Electrical Equipment	4.1	0.2				
3695	Magnetic & Optical Recording Equipment	43.6	0.6	43.6	0.6		
3699	Electrical Equipment & Supplies	78.0	4.1	78.0	4.1		
3693	X-Ray Apparatus (3844, 3845)	0.0	0.0				
3800	Instruments & Related Products	1.0	0.0	1.0	0.0		
3810	Search & Navigation Equipment	1.8	0.0	1.8	0.0		
3811	Engineer and Scientific Equip. (3812, etc)	1.9	0.0	1.9	0.0		
3812	Search & Navigation Equipment	785.5	3.5	785.5	3.5		
3820	Measuring & Controlling Devices	33.9	0.1	33.9	0.1		
3821	Laboratory Apparatus & Furniture	2.3	0.0	2.3	0.0		
3822	Environmental Controls	21.1	0.3	21.1	0.3		
3823	Process Control Equipment	274.8	1.6	274.8	1.6		
3824	Fluid Meters & Countig Devices	5.5	0.1	5.5	0.1		
3825	Electricity Measuring Instruments	146.6	1.0	146.6	1.0		
3826	Analytical Instruments	47.9	2.0	47.9	2.0		
3827	Optical Instruments & Lenses	92.3	1.1	92.3	1.1		
3829	Measuring & Controlling Devices, nec	50.3	0.3	50.3	0.3		
3830	Optical Instruments (3826)	11.7	0.0	11.7	0.0		
3832	Optical Instruments (3826)	0.6	0.0	0.6	0.0		
3840	Medical Instruments & Supplies	17.7	0.1	17.7	0.1		
3841	Surgical & Medical Instruments	245.2	2.9	245.2	2.9		
3842	Surgical Appliances & Supplies	87.5	0.6	87.5	0.6		
3843	Dental Equipment & Suppplies	21.6	0.2	21.6	0.2		
3844	X-Ray Apparatus & Tubes	6.7	0.1	6.7	0.1		
3845	Electromedical Equipment	52.7	0.7	52.7	0.7		
3850	Opthalmic Goods	1.1	0.0	1.1	0.0		
3851	Opthalmic Goods	61.8	1.0	61.8	1.0		
3860	Photographic Equipment & Supplies	7.5	0.0	7.5	0.0		
3861	Photographic Equipment & Supplies	89.5	2.6	89.5	2.6		
3870	Watches, Clocks, Watchcases, & Parts	0.2	0.0	0.2	0.0		
3873	Watches, Clocks, Watchcases, & Parts	3.0	0.0	3.0	0.0		
8220	Colleges & Universities	210.7	0.1			[2]	[2]
8221	Colleges & Universities	1631.7	83.4			[2]	[2]
8222	Junior Colleges	515.5	17.8	515.5	17.8		
8223	Private College & Prof's School (PG&E)	342.7	8.0	342.7	8.0		
8224	Private Jr. College and Tech. School (PG&E)	3.9	0.0	3.9	0.0		
8000	Health Services	2.5	0.0	2.5	0.0		
8050	Nursing & Personal Care Facilities	73.2	0.4				
8051	Skilled Nursing Care Facilities	257.0	9.9				
8052	Intermediate Care Facilities	8.7	0.7				
8059	Nursing & Personal Care Facilities	198.0	21.4				
8060	Hospitals	282.5	0.6	282.5	0.6		

				Contains Labs		*Predominantly Labs*	
SIC	Code Description	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)	**Elect.** (GWh)	**Gas** (10^{11} Btu)
8061	Medical and Surgical Hospital < 100 beds (PG&E)	114.7	5.0	114.7	5.0		
8062	General Medical & Surgical Hospitals	2329.2	91.3	2329.2	91.3		
8063	Psychiatric Hospitals	101.6	31.8				
8064	Medical & Surgical Hospital > 100 beds (PG&E)	763.3	47.8	763.3	47.8		
8065	Psych. Hospital < 100 Beds (PG&E)	4.6	0.1				
8066	Psych Hospital > 100 Beds (PG&E)	27.2	4.5				
8067	Specialty Hospital < 100 Beds (PG&E)	4.5	0.2	4.5	0.2	4.5	0.2
8068	Specialty Hospital > 100 Beds (PG&E)	17.9	0.4	17.9	0.4	17.9	0.4
8069	Specialty Hospitals, etc. Psychiatric	80.5	3.2				
8070	Medical & Dental Laboratories	8.9	0.0	8.9	0.0	8.9	0.0
8071	Medical Laboratories	140.3	1.3	140.3	1.3	140.3	1.3
8072	Dental Laboratories	16.8	0.3	16.8	0.3	16.8	0.3
8080	Home health care Services	1.6	0.0				
8081	Outpatient Care Faciltity (8011, etc.)	5.7	0.0				
8082	Home health care Services	20.8	0.2				
8090	Health & Allied Services	13.1	0.0				
8091	Health& Allied Services NEC (8082, 8099)	10.5	0.0				
8092	Kidney Dialysis Centers	14.0	0.1				
8093	Specialty Outpatient Clinics, nec	51.3	0.8				
8099	Health & Allied Services	83.1	1.8				
8010	Offices & Clinics of Medical Doctors	59.2	0.0				
8011	Offices & Clinics of Medical Doctors	945.8	19.6				
8020	Offices & Clinics of Dentists	8.4	0.0				
8021	Offices & Clinics of Dentists	203.6	2.6				
8030	Offices of Osteopathic Physicians	0.0	0.0				
8031	Offices of Osteopathic Physicians	1.2	0.0				
8040	Offices of Other Health Practitioners	5.8	0.0				
8041	Offices & Clinics of Chiropractors	41.6	0.7				
8042	Offices & Clinics of Optometrists	30.4	0.3				
8043	Offices & Clinics of Podiatrists	3.6	0.1				
8049	Offices of Health Practitioners	52.6	0.7				
8731	Commercial Physical research	533.7	8.3				
8734	Testing Laboratories	125.8	0.9	125.8	0.9	125.8	0.9
	Subtotal, in original units (N=253)	23095	758	13206	323	4952	95
Adjustments							
	University & College Labs	450	30	450	30	450	30
	[Based on 5-campus study described in Section IV and AppendixC with a ~30% upward adjustment factor to approximate full UC and state college system (for which data are not available)]						
	DOE Facilities (LBNL, LLNL, SLAC) [3]	648	7	648	7	648	7
	Totals, in original units	23743	765	14304	361	6050	132
	Central Estimate, in original units (weighted average of data columns 3-6)					**8774**	**207**

Totals for Laboratory-Type Facilities	Total 1993	Energy Cost ($M)	Total 2015	Energy Cost* ($M)	Percent Growth	Annual Growth Rate
Total Energy (TBTU)	111	700	255	1640	131%	3.9%
Electricity Consumption (GWh)	8774	644	20782	1525	137%	4.0%
Electrical Generating Capacity (GW)	2.1		4.9		137%	4.0%
Natural Gas (TBTU)	21	56	43	116	106%	3.3%

** Assuming frozen efficiency, defined as constant energy use per unit of shipments for each sector*

1993 Laboratory total energy as a fraction of total electricity in SIC 2700-8734 category	35%
1993 Laboratory electricity as a fraction of total electricity in SIC 2700-8734 category	38%
1993 Laboratory natural gas as a fraction of total electricity in SIC 2700-8734 category	27%

Frozen-Efficiency Scenario

2015 Laboratory total energy as a fraction of total electricity in SIC 2700-8734 category	40%
2015 Laboratory electricity as a fraction of total electricity in SIC 2700-8734 category	43%
2015 Laboratory natural gas as a fraction of total electricity in SIC 2700-8734 category	29%

Assumptions

Electricity Price [Industrial sector average]	$0.073	per kWh	
Natural Gas Price [Industrial sector average]	$0.272	per 100 kBTU	
Energy Savings achieved by 2015	50%		
Heat Rate for Source Electricity (Btu/kWh)	10239		
Electric Capacity Factor (CA average)	0.48	-->	4.2 BkWh/GW
(Electric Reserve Margin)	25%		
(Transmission & Distribution Losses)	8%		

Interpolation Factor (weighted midpoint between "Predominantly Labs" and "Contains Labs") 0.33
[i.e. 33% of the energy use in the “Contains Labs” category is allocated to laboratory-type facilities. This implies a relatively small fraction of floor area, ranging from 1%-7% depending on the laboratory energy intensity.]

Notes:

[1] Energy use by SIC: California Energy Commission, Personal Communication, Andrea Gough, Sept. 8, 1995.

[2] University Data: Marton Associates (Berkeley, CA). Utilities Cost Allocation Studies. UCLA (6/1992 and 3/1994), UCB (12/88), UCSD (12/88), UCI (3/87), UCSF (5/87).

[3] Energy sold to the National Laboratories (LBNL and LLNL) not counted consistently in CEC energy stat's. The problem arises because the facilities purchase power from more than one utility, and reporting utilities do not always use the same SIC number to describe a given facility. LBNL purchases power from PG&E and WAPA and Lawrence Livermore National Lab purchases from Pacific Corp, WAPA, and PG&E. Per account rep. George Alfaro, PG&E has assigned LBNL with SIC 8731. However per WAPA (Loretta Hertzig), LBNL, LLNL (and SLAC) are assigned 8920; PG&E codes LLNL as 8733.

APPENDIX B
Efficiency Options and Savings Potential in Cleanrooms

Energy Savings Potential in California Cleanrooms

Utilizing the types of strategies described below and elsewhere can yield in excess of 70% energy savings in cleanrooms.* The potential for California is described in **Table 6** and in **Table B-1** below.

Table B-1. Annual HVAC Energy use of California Cleanroom Facilities.

	Typical	High Efficiency	
Motor Efficiency:	85%	94%	
Fan Efficiency:	65%	90%	
Static Pressure Drop	5	2	• Inches of water column (w.c.)
Equiv. Full-Load Hours of Operation	8700		• Very minimal fan downtime, even when process is interrupted

Assumptions (Cooling; Heating)	Cooling	(high-efficiency)	Heating	(high-efficiency)
design ΔH (enthalpy) Btu/ft^3	2.5		0.9	
season hours > Tbal; < Tbal	2500		6260	
seasonal load factor (energy-weighted), hrs @ given load	0.4		0.3	
HVAC kW/ton; HVAC Efficiency	1.8	0.8	0.56	0.7
tons/BtuH; therms/Btu	8.333x10^{-05}		1x10^{-05}	
CFM/sf (outside air)	5	1	5	1

			Cleanroom Class			Totals
	1 and 10	**100**	**1000**	**10,000**	**100,000**	**or Avg's.**
U.S. floor space, million ft^2, 1993	4.73	10.07	9.57	8.34	10.98	**44**
U.S. floor space % by class.	11%	23%	22%	19%	25%	**100%**
Calif floorspace, frac. of US market	30%	20%	10%	10%	10%	**14%**
California floor space million ft^2	1.42	2.01	0.96	0.83	1.10	**6.3**
Static Pressure Drop (inches w.c.)	5.00	5.00	5.00	5.00	5.00	**5**
CFM/ft^2 -- recirculation	90	70	30	10	5	**49**
CFM/ft^2 - OA (cooling)	5	5	5	5	5	**5**
CFM/ft^2- OA (heating)	5	5	5	5	5	**5.00**
Total CFM (10^6)	128	141	29	8	5	**311**
Air Changes per Hour [8-foot ceiling]	675	525	225	75	38	**369**
Energy Use (Typical cleanrooms)						
Heating therms/yr-ft^2	9.13	9.13	9.13	9.13	9.13	**9.127**
Cooling kWh/yr-ft^2	113	113	113	113	113	**112.5**

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* For an in-depth exploration of efficiency options in prototypical cleanrooms, see Supersymmetry Services Pte Ltd, Singapore. 1994. *Energy Audit Report: Opportunities for Improved Energy Efficiency at ABC Electronics Corp.*

Cleanroom Class:	1 and 10	100	1000	10,000	100,000	Totals or Avg's.
Outside air heating (10^{12} BTU/yr)	1.294	1.838	0.873	0.761	1.002	**5.77**
Outside air cooling (GWh/year)	160	227	108	94	123	**711**
Outside air cooling load (MW)	18	26	12	11	14	**81**
Fan Power (W/ft^2)	96	74	32	11	5	**52**
Fan Energy (kWh/ft^2-year)	832	647	277	92	46	**455**
Fan Load (MW)	136	150	31	9	6	**331**
Fan Energy (GWh)	1181	1304	266	77	51	**2878**
Total Electricity Intensity (Fan + Cooling) [kWh/ft^2-year]	945	760	390	205	159	**568**
HVAC Load from Fan Work (MW)	69	77	16	5	3	**169**
HVAC Energy from Fan Work (GWh)	604	667	136	39	26	**1472**
Total Energy (MW, incl CA avg. 48% capacity factor)	465	526	122	50	48	**1211**
Total Energy (GWh)	1944	2198	509	210	200	**5061**

Notes

- Airflow velocity updates are taken from Chapter 7 (Class 1&10 to 90 fpm, Class 100 to 70 fpm, Class 1,000 to 30 fpm, Class 10,000 to 10 fpm, and Class 100,000 to 5 fpm) *Cleanrooms - 1992-2000, Rooms and Components* Vol. Three. McIlvaine, Robert W., Sally Halderman, Alpa Bagga, and Joseph Schwartz, eds. City, State: The McIlvaine Co., 1992. Chapter 1, Rooms; Chapter 4, Engineering & Design.
- Outside air air estimates for cleanroom make-up air (5 cfm/sq.ft. for both heating and cooling): Brown, W.K., PE. "Makeup Air Systems Energy-Saving Opportunities." *ASHRAE Transactions* V. 96, 1990.

Advanced Technologies for HVAC in Cleanrooms

1) High-efficiency (e.g. 95%), low-noise fans.

2) Active noise cancellation methods to reduce pressure drops in passive/absorber silencers.

3) Use of high and low temperature chillers to optimize chiller kW/T, e.g. 42 deg. F chillers @ 0.600 kW/ton for outside air, and 60 deg. F chillers @ 0.30 kW/ton for recirculation air.

4) Use of low face velocity/high coolant velocity cooling coils to reduce pressure drops.

5) Electrostatic elements in filters to increase efficiency while reducing pressure drops.

6) Use of heat exchange methods to recover coolth from typically large exhaust air streams to makeup air e.g. heat pipes, counter/cross flow heat exchangers.

7) Use of low-pressure drop filters, achieved by use of large face areas, lower air velocities, pleated media without aluminum or other spacers, lower-pressure-drop media, etc.

8) Use of automation and other mini-environment technologies to reduce area of clean zones and hence air flow.

9) Use of computational fluid dynamics (CFD) to model air flows, effects of convection from heat sources, etc. as part of design process.

10) Use of distributed particle counters with digital interfaces to monitor cleanroom conditions and appropriate settings for velocity, temperature, humidity, etc.

11) Minimum downward velocity needed to overcome heat convection, movement of people, conveyors, etc. Even light emanating from a light fixture can create upward currents of air - which potentially causes contamination.

12) High-pressure-drop filters to restrict airflow in those areas not needing more velocity.

13) The production of de-ionized water for cleanrooms in pharmaceutical and semiconductor industries is very energy intensive, and can be addressed with various efficiency strategies.

Reduced Plug Loads in Cleanrooms: Example of Notebook Computers as Replacement for Desktop Computers

The following measures address the use of notebook computers instead of normal computers and monitors where needed for test equipment or as controllers for automation, conveyors, etc. in cleanrooms.

1) Usually semiconductor test/automation equipment is on a UPS or line conditioner, which cost US$1/- per VA or more. Going from the 150VA of PC to 5VA or less of notebooks saves over US$100 in electrical infrastructure costs.

2) Desktop PC have fans for cooling. These disturb the laminar air flow and cause contamination, and induce diffusion of dirt from within the computer.

3) Regular monitors have ventilation holes, through which dirt can escape into the cleanroom.

4) Monitors have an electrostatic charge on the screen, which attracts dust and creates static.

5) The heat load of 150VA causes a convection column of hot air which upsets the vertical laminar downflow and increases the particle count, requiring incrementally more fan speed.

6) Substantial cooling load of PC necessitates more air-handler units, chillers, etc.

7) Energy savings calculations should take account of UPS efficiency also, say 85% ~ 95% depending on model and load.

Applications for Remote Lighting Systems in Cleanrooms

Remote lighting systems (e.g. fiber optics or light guides) offer an opportunity for energy savings by enabling the use of high-efficiency sources (e.g. the sulfur lamp) not practical for ordinary fixture types. As is often the case with end-use efficiency technologies, remote lighting systems also offer specific potential non-energy benefits, as illustrated below.

1) Ballasts, starters, wiring, etc. are outside the “clean/sensitive” environment. Downtime is extremely costly and maintenance within the clean environment is far costlier than in ordinary environments.

2) EMI/RFI is reduced, especially from electronic ballasts. Sensitive test equipment is adversely affected by EMI/RFI.

3) Pharmaceutical laboratories employ steam cleaning or swabbing with aggressive chemicals that are detrimental for ordinary luminaries.

4) Normal tear-drop fixtures occupy a lot of ceiling depth - a problem in many applications.

5) Avoids outgassing of undesirable chemicals, always a problem with ballasts, capacitors, starters. The contacts (pinholders) shed carbon and other electrically-attacked materials.

6) Heat emissions from ordinary lighting systems cause upwelling air currents and interfere with intended airflow patterns.

7) Reduced heat load - saves on first cost of air-handler units, chillers, etc.

8) Reduced turbulence in air flow — custom aerodynamic shapes are possible with light pipes.

9) Better optical control/efficiency — normal teardrop fittings are only 60mm wide (so as to avoid interference with HEPA filter array across ceilings) and have no space for reflectors.

10) Easier (i.e., due to fewer light sources) to change intensity/color e.g. yellow light for photomask/litho

11) Fast install/dismantle using special inserts on light pipes into HEPA filter grid - no wires, etc.

12) Can extrude from special materials e.g. conductive plastics.

13) Reduced crevices/gaps to harbor bacteria/virus/particles/gases.

14) Lamp shattering risk is eliminated.

15) Acoustically quiet - may be needed for certain tests.

16) Possible integration with other services e.g. loudspeakers, using piezoelectric drivers to make entire light pipe surface radiate sound (technology already sold for walls and windows speakers).

17) Precision illumination - with the trend towards establishing minienvironments within larger laboratories, energy savings opportunities will arise from delivering illuminance more strategically and precisely to the area where critical tasks are being performed. In some cases it will be possible to relax illuminance requirements in surrounding areas. Fiber optic systems offer flexibility in situations where the location of the task may change from time to time (i.e. assuming the fiber optic cables are easier to relocate than ordinary luminaries).

APPENDIX C

Derivation of University of California Laboratory Energy Use Estimates

This appendix describes the methodology used to evaluate energy use in University of California laboratory-type facilities. The results for five campuses are detailed in **Table C-1**. The description is based on the approach used at UCLA, the methodology was identical for all five studies, except for minor improvements and streamlining.*

Table C-1 Detailed Data on Laboratory and Non-Laboratory Energy Use in University of California Campuses.

CAMPUS/ YEAR	RESEARCH SPACE CATEGORIES	ROOMS	ASF	KWH/ASF,YR	ELECTRICITY MWH/YR	GAS TU/ASF,YR	NATURAL GAS MBTU/YR	LABS ELECT AS % OF TOTAL	LABS GAS AS % OF TOTAL
UCLA	ANIMAL SPACES	267	61,151	66.33	4,056	11.28	68,961		
92/93									
	TEACHING LABS	303	186,712	54.27	10,133	4.25	79,304		
	LAB OFFICES, ENG & SCI	455	117,546	73.62	8,654	6.90	81,051		
	LABS & SERV, ENG & PHYS SCI	405	237,386	111.43	26,451	8.16	193,746		
	LABS & SERV, LIFE & HLTH SCI	2,836	713,617	124.25	88,665	7.73	551,782		
	TOTAL / AVG, LAB	4,266	1,316,412	104.80	137,958	7.41	974,844		
	TOTAL / AVG, NON-LAB	16,312	4,416,450	24.92	110,076	1.67	735,847		
	TOTAL / AVG, CAMPUS	20,578	5,732,862	43.27	248,034	2.98	1,710,691	56%	57%
UCB	ANIMAL SPACES, EXIST BLDGS	156	25,207	42.68	1,076	6.64	16,741		
91/92	ANIMAL SPACES, 4 NEW BLDGS	153	23,978	50.34	1,207	6.00	14,379		
	TOTAL / AVG, ANIMAL SPACES	309	49,185	46.41	2,283	6.33	31,119		
	TEACHING LABS	323	207,169	17.38	3,600	1.30	26,977		
	TEACHING LABS (New)	12	8,665	50.83	440	3.90	3,383		
	TOTAL/AVG, TEACHING LABS	335	49,185	18.72	4,040	1.41	30,360		
	LAB OFFICES, EXIST BLDGS	216	61,365	32.38	1,987	2.42	14,877		
	LAB OFFICES, 4 NEW BLDGS	17	3,114	61.63	192	6.22	1,937		
	TOTAL / AVG, RES OFFICES	233	64,479	33.79	2,179	2.61	16,814		
	LABS, ENG & PHYS SCI	854	444,251	62.06	27,572	4.80	213,278		
	LAB SERV, ENG & PHYS SCI	348	82,641	72.51	5,992	3.36	27,790		
	TOT / AVG, ENG & PHYS SCI	1,202	526,892	63.70	33,564	4.58	241,069		
	LABS, LIFE & HLTH SCI, EXIST	618	193,696	61.82	11,974	5.98	115,785		
	LABS, LIFE & HLTH SCI, 4 NEW	310	114,691	79.00	9,061	4.28	49,104		
	LAB SERV, LIFE & HLTH SCI, EXIST	340	62,761	69.19	4,342	7.08	44,453		
	LAB SERV, LIFE & HLTH SCI, 4 NEW	204	23,089	109.74	2,534	4.59	10,587		
	TOT / AVG FOR LIFE & HLTH SCI	1,472	394,237	70.80	27,911	5.58	219,930		
	TOTAL / AVG, LAB	3,551	1,250,627	55.95	69,976	4.31	539,291		
	TOTAL / AVG, NON-LAB	11,351	4,406,938	14.92	65,738	0.96	422,814		
	TOTAL / AVG, CAMPUS	14,902	5,657,565	23.99	135,714	1.70	962,105	52%	56%

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*Marton Associates. *Utilities Cost Allocation Studies*. UCLA (6/1992 and 3/1994), UCB (12/88), UCSD (12/88), UCI (3/87), UCSF (5/87). Berkeley, California.

CAMPUS/ YEAR	RESEARCH SPACE CATEGORIES	ROOMS	ASF	KWH/ASF,YR	ELECTRICITY MWH/YR	GAS TU/ASF,YR	NATURAL GAS MBTU/YR	LABS ELECT AS % OF TOTAL	LABS GAS AS % OF TOTAL
UCSD 87/88	ANIMAL SPACES	191	45,235	46.03	2,082	6.97	31,538		
	TEACHING LABS	146	94,163	33.30	3,135	2.51	23,623		
	LAB OFFICES, ENG & SCI	158	23,129	27.78	643	1.59	3,667		
	LABS, ENG & PHYS SCI	314	160,853	52.64	8,467	2.88	46,403		
	LAB SERV, ENG & PHYS SCI	137	31,694	40.17	1,273	2.85	9,041		
	TOT / AVG, ENG & PHYS SCI	451	192,547	50.58	9,740	2.88	55,443		
	LABS, LIFE & HLTH SCI	837	307,846	88.87	27,359	5.14	158,209		
	LAB SERV, LIFE & HLTH SCI	464	76,749	105.14	8,070	6.75	51,748		
	TOT / AVG, LIFE & HLTH SCI	1,301	384,595	92.12	35,429	5.46	209,957		
	TOTAL / AVG, LAB	2,247	645,652	79.03	51,028	5.02	324,229		
	TOTAL / AVG, NON-LAB	5,381	1,485,130	24.05	35,962	1.31	196,447		
	TOTAL / AVG, CAMPUS	7,628	2,140,782	40.63	86,990	2.43	520,676	59%	62%
UCI 86/87	RES ANIMAL SPACES	76	13,019	62.77	817	14.81	19,287		
	TEACHING LABS	132	65,672	41.40	2,719	2.06	13,521		
	RES LAB OFFICES, ENG & SCI	43	6,980	61.07	426	5.29	3,695		
	RES LABS, ENG & PHYS SCI	94	67,008	111.78	7,490	2.89	19,355		
	RES LAB SERV, ENG & PHYS SCI	36	7,576	120.33	912	2.24	1,700		
	TOT / AVG, ENG & PHYS SCI	130	74,584	112.65	8,402	2.82	21,055		
	RES LABS, LIFE & HLTH SCI	393	139,540	103.20	14,401	7.63	106,462		
	RES LAB SERV, LIFE & HLTH SCI	294	44,528	98.98	4,408	8.74	38,895		
	TOT / AVG, LIFE & HLTH SCI	687	184,068	102.18	18,808	7.90	145,357		
	TOTAL / AVG, LAB	1,068	344,323	90.53	31,173	5.89	202,915		
	TOTAL / AVG, NON-LAB	2,616	836,132	23.64	19,765	1.13	94,445		
	TOTAL / AVG, CAMPUS	3,684	1,180,455	43.15	50,938	2.52	297,360	61%	68%
UCSF	ANIMAL SPACES WITH HVAC	71	18,713	43.39	812	7.74	14,488		
86/87	ANIMAL SPACES WITH H &/or V ONLY	75	16,353	21.51	352	3.56	5,821		
	TOT / AVG, ANIMAL SPACES	146	35,066	33.19	1,164	5.79	20,309		
	TEACHING LABS	124	50,619	16.23	821	3.67	18,557		
	LAB OFFICES	126	20,277	25.32	513	3.30	6,689		
	LABS WITH HVAC	84	21,373	136.19	2,911	5.73	12,242		
	LABS WITH H &/or V ONLY	870	246,372	64.73	15,948	4.57	112,699		
	TOT / AVG, LABS	954	267,745	70.44	18,859	4.67	124,941		
	LAB SERV WITH HVAC	61	9,805	60.34	592	3.90	3,823		
	LAB SERV WITH H &/or V ONLY	642	77,105	47.17	3,637	3.88	29,914		
	TOTAL/ AVG, LAB SERV	703	86,910	48.66	4,229	3.88	33,737		

CAMPUS/ YEAR	RESEARCH SPACE CATEGORIES	ROOMS	ASF	KWH/ASF,YR	ELECTRICITY MWH/YR	GAS TU/ASF,YR	NATURAL GAS MBTU/YR	LABS ELECT AS % OF TOTAL	LABS GAS AS % OF TOTAL
FIVE-CAMPUS TOTAL	TOTAL / AVG, LAB	2,053	460,617	55.55	25,586	4.43	204,233		
	TOTAL / AVG, NON-LAB	3,820	705,129	17.60	12,412	2.17	153,178		
	TOTAL / AVG, CAMPUS	5,873	1,165,746	32.60	37,998	3.07	357,410	67%	57%
	TOTAL / AVG, LAB	13,185	4,017,631	78.58	315,722	5.59	2,245,512		
	TOTAL / AVG, NON-LAB	39,480	11,859,779	20.57	243,952	1.35	1,602,729		
	TOTAL / AVG, CAMPUS	52,665	15,877,410	35.25	559,674	2.42	3,848,242	56%	58%

ASF = Assignable Floor Area, sq. ft.
TU = Thermal Unit ("therm") = 100,000 BTU, a commercial energy unit used for natural gas.
The term "CAMPUS" refers to buildings included in the specific study only, typically consisting of on-campus academic buildings. Student housing units, non-research off-campus buildings, and separately metered on-campus non-academic buildings were generally excluded. Hospitals not included.

The purpose of these studies was to establish the level of electricity and fossil fuel usage in the various research and non-research room types. The results were intended as the basis for determining the utilities-related components of the overhead rates associated with different room types and occupant activities.

Basic principles, goals, and quality indicators of the project were:

- A large number of randomly selected rooms represented a good cross section of the room types found on the Campuses.

- Categories were carefully developed to group together spaces with similar characteristics prior to random selection of the survey samples.

- The survey and analytical methodology was identical for every sample room and Campus.

- Estimates of the yearly electrical and fossil fuel consumption were derived by combining survey data for sample rooms with a sophisticated building energy computer program, which simulated each room for each hour of the base year using actual hourly temperatures logged at the site.

- The metered electric and gas consumption and cost data for the buildings included in the study were carefully derived from detailed documentation provided the universities.

- The electrical and fossil fuel campus totals derived from the sample room results are in close agreement with the corresponding metered campus totals.

- Statistical significance tests performed on the results were satisfactory for all room categories, indicating that the room samples were highly representative of all assignable rooms in the study.

Survey Method

The survey phase consisted of the detailed survey of each sample room, the collection of operational data of air conditioning fan rooms and central boiler and chiller plants and the gathering of non-assignable floor area energy usage data.

Research related room categories, which tend to be diverse, had relatively large samples, i.e., in the 20% range. On the other hand, the relatively uniform and large academic office category was represented with a sample of only 1.5% of all such rooms, in accordance with expectations based on past similar studies completed at UCLA.

The computer category sample was more than 60%, since it was expected that a statistically valid sample cannot be smaller from this rather diverse and relatively small category. The diversity in energy usage is due to some rooms containing mainframe systems, while others are terminal rooms, PC rooms for students, or tape storage spaces.

Statistical tests were applied to the category results in order to show that the room samples were sufficiently representative of all assignable rooms. A site- and year-specific weather tape containing hourly data was also developed and utilized in the analysis based on hourly outside air temperature readings collected at the UCLA boiler plant by UCLA personnel.

The following provides additional description of the specific room categories:

1. ANIMA, laboratory animal quarters and service spaces in support of life and health science research; nearly all air conditioned with high air change rates; 100% fresh air systems operating at all times.

2. CLBES, class laboratories in engineering and physical and life and health science departments; energy usage is higher than non-science instruction spaces, but lower than in spaces of organized research.

3. CMPTR, computer spaces; relatively small category with a mixture of high and low energy intensity rooms (mainframe system rooms vs. terminal rooms, PC rooms or tape storage.

4. CLROT, classrooms and class labs and research spaces not in categories CLBES, RLEPS or RLLHS.

5. HOSPT, hospital spaces; patient care, special care and service rooms within the large medical school complex at UCLA.

6. LIBRA, library spaces; stacks, reading rooms, study rooms and carrels, low equipment loads compensated with long hours for lights.

7. MISCE, miscellaneous non-academic spaces; all non-academic rooms not in the other categories.

8. OFACA, academic offices, excluding research offices within laboratory complexes.

9. OFOTH, other offices; administrative and service offices.

10. OTACA, other academic spaces; miscellaneous academic spaces not sorted into either of the other categories.

11. OFRES, research offices in the engineering and physical and life and health science fields; nearly always within suites of research rooms (laboratories).

12. RLEPS, research laboratories and laboratory service rooms in engineering and physical science fields.

13. RLLHA, research laboratories and laboratory service rooms in life and health science fields.

Selection of Room Samples for Auditing and Energy Analysis

A random sample was chosen from each room category using the following procedure and considerations:

- First, the rooms within each category were sorted by building name and room numbers forming the initial sequence or ranking of the rooms.

- Next, the random number generator of the LBL VAX system was utilized to assign a second, randomly selected rank number to each room within each category.

- In the third step, the categories were re-sorted by the random rank numbers ready for selecting category samples of any size starting with the room that is the first in the random sequence and ending with the room whose random rank number equals the desired sample size.

- In the next step, the total of 2,400 sample rooms was subdivided into the category samples. The final sample sizes, which add up to 2286, or 4.75% less than the planned sample (in the case of UCLA). The missing sample rooms were either inaccessible or could not be located during the surveys. In most cases, this was due to ongoing or recently completed construction and demolition projects.

- Three factors influenced the selection of sample sizes for the individual categories based on experience gained in 1982-83 and 1986-87 studies: the expected room-to-room diversity in energy usage, the general level of activity in the rooms, and the category size. Category sizes had an inverse effect on the relative size of samples.

- Since the relatively small computer spaces category, CMPTR, was expected to be diverse, it was decided to survey 60% of this category.

Energy Audit Procedure

The survey of each sample room consisted of the collection of energy usage related information in a uniform manner covering all items on the survey form. Steps of room surveys were the following:

- Where possible, the surveyor met the designated representative of the department occupying the building or part of a larger building. This person was usually familiar with the building operation, was known by the occupants of the sample rooms, had a master passkey, and acted as escort to the auditors.

- The rooms were surveyed, according to the following:

    - Checking and augmentation of room data extracted from Campus' room databases, including function of room, room area, ceiling height, whether the room is exterior or interior and others.

  - Measuring the dimensions and establishing the materials and shading of all exterior surfaces (roofs, walls, windows and doors).
  - Recording all lighting loads.
  - Recording all electrical and thermal (steam and natural gas) equipment loads.
  - Recording people or research animal thermal loads (significant in lecture halls and research animal holding rooms).
  - Checking and recording whether the room had forced air ventilation or was air conditioned.
- Short interviews were conducted with the occupants of each room regarding the operating schedules of the lights, electrical and thermal equipment and people in the room. The information was attained from department administration staff where the occupants were not available.

Building level HVAC, central plant and public area usage data (non-assignable floor area usage) was collected in addition to the room surveys and in follow-up inquiries, including the following items:

- Operational data of building HVAC systems and heating and cooling plants was collected in the course of meetings with Facilities Management staff, including plant engineers and field supervisory personnel.
- Data was requested and collected pertaining energy usage outside of assignable rooms (non-asf usage), including:
  - Compressed air and vacuum systems serving laboratories.
  - Laboratory fume hood and other safety hood systems.
  - Process steam end-use devices serving life and health science laboratories (autoclaves, etc.)
  - Streets, grounds and parking lighting.
  - Building elevators.
- The total electrical and fossil fuel metered totals and energy unit costs were collected for the buildings included in the study. Fossil fuel included natural gas and fuel oil.
- Hourly outside air temperature data logged at the steam plants was also obtained for use in conjunction with computer analysis of the sample rooms.

The processing of the data consisted of the following:

- A special pre-processor code was adapted and updated. This FORTRAN program creates a separate DOE-2 input model for each of the surveyed rooms from the collected data and has the following features:

  - It prompts for the keyboard entry of data in a logical sequence until all applicable data is entered directly from the survey forms.

  - It sums for each hour of the year the lighting, electrical and fossil equipment loads and internal heat gains from the entered data. The result is a composite schedule for each load type.

  - It writes an input file for each room in the language of the DOE-2 program.

- The room survey data was key-punched creating a separate DOE-2 input file for each survey room.

- HVAC system and central heating/cooling plant models were produced for each building, or group of similarly served rooms within a building, and were merged with the room models from the preprocessor code. The parameters used in the models of systems and plants included such items as the HVAC system type, fan operating hours, ventilation rate, amount of fresh air, temperature settings, boiler efficiency and others.

Physical data collected during the audits included:

- Size, orientation and materials of exterior surfaces

- Lighting loads and schedules

- Type, load and schedules of electrical and thermal equipment in the room

- Heating, ventilating, and air conditioning (HVAC) supply air flow, where measurable

- Other energy usage and HVAC-related data and observations.

- Preparation of a list of the central systems and campus level data to be collected, including:

  - Description, operational parameters and schedules of the HVAC systems and steam and chilled water plants serving the buildings, to be used in the computer analysis of the heating, cooling and ventilating energy consumption of the sample rooms.

  - Category-specific building level (non-asf) data for energy usage not directly associated with individual rooms, such as compressed air and vacuum systems.

  - Campus and building level (non-asf) data covering general energy usage not directly related to the rooms, such as street lighting loads, lights and HVAC service in non-asf areas of buildings (corridors and other public areas), elevators, hot water service to public areas, and others.

Category specific non-asf usage accounted for the following building level special electrical, fuel, and steam equipment and systems:

- Electrical equipment or systems serving engineering and physical, life and health sciences spaces, allocated to categories RLEPS and RLLHS:

  - Laboratory compressed air and vacuum systems

    - Laboratory fume, biological and clean hood blower systems mostly located on roofs
    - Cleanroom scrubbers and fans
    - Process cooling
- Fossil fuel users:
    - Life and health sciences related process steam usage allocated to categories ANIMA, CLBES, HOSPT and RLLHS (steam autoclaves, washers, dryers and distillers)
    - Gas burning incinerators serving life and health science departments (categories ANIMA, HOSPT and RLLHS)

General non-asf usage consists of items that are not related specifically to any of the room categories, such as corridor lights. Each of these items was allocated to the room categories based on average usage per assignable floor area (asf).

The following general usage items were allocated on an assignable square footage basis:

- Electrical systems:
    - Corridor and public area lighting
    - Street and grounds lighting
    - Building elevators
    - Water coolers
    - HVAC control air compressors
    - Power distribution losses
- Fossil fuel based systems:
    - Fuel for domestic hot water to public areas
    - Corridor and public area HVAC services
    - Steam distribution losses

Energy Analysis Methodology

The energy analysis consisted of the following four components:

- The first component consists of the electric and fuel results computed for each category from the survey data of the sample rooms. These represent 80% of the total usage, consisting of the actual consumption within assignable rooms plus the energy consumed of the heating, ventilating and air conditioning (HVAC) services to the same rooms.

- The second component consists of category specific non-asf usage, i.e., energy consumed by certain building level utility systems dedicated to specific room categories, such as laboratory compressed air systems.

- The third component consists of general non-asf usage, such as corridor lights, that is allocated to all categories in proportion to their floor areas.

- The fourth component consists of campus-wide distribution losses estimated to be 5% for electricity and 10% for steam.

The sum of the above four components yields the computed electric and fossil fuel energy consumption. The results were computed with DOE-2.1d, an hourly simulation model, DOE-2, developed and maintained at the Lawrence Berkeley National Laboratory.

The criterion for accuracy of the work was that for each category sample the tolerance of the mean of room energy usage had to be no greater than 15% at a 90% level of confidence. In this context, tolerance is analogous to half of the confidence interval for the mean. A given category satisfies the prescribed test if the limits of the confidence interval computed from its sample at a 90% confidence level are no less than 85% and no greater than 115% of the sample mean. The interpretation of this is that if a large number of subsequent samples of the same size were analyzed, for 90% of the samples the confidence interval could be expected to enclose the category mean. All categories passed the tests, i.e., the “tolerance” defined earlier in this section was less than 15%. For several categories the tolerance was much less than 15%.

APPENDIX D

Structure of *A Design Guide for Energy Efficient Research Laboratories*

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