

Measuring and Managing Cleanroom Energy Use

Findings—and resulting best practices—from
a study of energy use in 28 cleanrooms

Combining high air-recirculation rates and energy-intensive processes, cleanrooms are 20 to 100 times as costly to operate on a per-square-foot basis as conventional commercial buildings. Additionally, they operate 24 hr a day, seven days a week, which means their electricity demand always is contributing to peak utility-system demand, an important fact given increasing reliance on time-dependent tariffs.

This article will discuss findings from an extensive study of energy use in 28 cleanrooms.¹

RIGHT-SIZING

Determining initial and projected loads in cleanrooms is a challenge. In some cases (e.g., cooling towers), upsizing enhances energy efficiency, while in many more, downsizing is the goal. One way to enable right-sizing is to minimize pressure drop in air- and water-based subsystems.

An extreme example of what can

happen in an ad-hoc design process when everyone adds an extra oversizing factor can be seen in Table 1. Safety factors and capacity-oversizing

requests should be stated clearly and conformed to by all disciplines, rather than allowed to grow haphazardly.

Best practices for right-sizing include:

- Having the design team

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Effective design value, watts per square foot	Cumulative safety/oversize factor	Design participant
50	1	Actual requirement. Typically, can be determined only by direct measurement after completion. Nameplate electrical data typically is the maximum startup value. Actual loads are significantly lower during operation.
100	2	Process engineers. A safety factor is added to allow for unknown future loads or equipment additions late in the design process. This also can include the influence of manufacturer's data, which often includes a large safety factor (particularly regarding exhaust rates).
100	2	Architect/mechanical and electrical engineer/general contractor. Typically, the process requirements, including any safety factors added by the process engineer, are passed directly to the engineers.
150	3	Mechanical engineer. To provide a design "safety factor," an additional 50- to 100-percent sizing factor is added. This influences design from chiller plant to coils to fans.
225	4.5	Electrical engineer. Oversized mechanical equipment also needs to be served fully, which has a noticeable impact on the total power requirements of a space. Electrical needs usually are determined based on the process engineer's input, the safety factors applied, equipment sizes rounded up, etc. The mechanical engineer sizes the HVAC equipment to remove the heat from these theoretical loads. Once the HVAC equipment is sized, the power requirements are given back to the electrical engineer.

TABLE 1. Impact of implicit oversizing creep.

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(owner, engineers, operations staff) explicitly agree on design loads and any margins to be used in design.

- Sizing equipment to avoid efficiency penalties at part-load conditions. Often, this will involve unequal unit sizing and/or a modular approach.

System	Typical pressure drop (total static pressure)	Best-practice pressure drop (total static pressure)
Recirculation air	1.5 to 3 in.	0.5 to 1 in.
Makeup air	6 to 10 in.	2 to 5 in.

TABLE 2. Pressure-drop design targets.

- Upsizing cooling towers, which represent a very small portion of plant energy consumption, to significantly improve chiller performance and water-side-free-cooling-system operation.

- Utilizing variable-frequency drives (VFDs) to realize operational savings from oversized fans, pumps, cooling towers, and some types of chillers.

- Designing and operating redundant air handlers, scrubbers, and cooling-tower units in parallel to reduce pressure drop and power requirements and to provide backup capacity.

- Employing methods such as medium-temperature cooling loops and water-side free cooling to eliminate the need for electric chillers during the lowest load periods of the year and, thus, mitigate the impact of oversizing.

The most efficient systems utilize upsized passive components (e.g., ducts and pipes), which allow the use of smaller fans and pumps. The smaller fans and pumps help to offset the additional first cost of the larger passive components and yield ongoing energy savings.

Because of reheating, boiler plants commonly operate throughout the summer. If reheat requirements cannot be eliminated through heat recovery, the use of boilers of different sizes with an intelligent seasonal switchover control is recommended to minimize idle-boiler energy use during low-load periods.

MINIMIZING PRESSURE DROP

Air-delivery-system pressure drop is the design parameter with the greatest impact on power requirements. Some general targets are offered in Table 2. Pressure drop in a duct or air handler is approximately proportional to the face velocity squared. Because fan power has

a linear relationship with pressure drop, similar reductions in fan sizing can be obtained with reduced pressure drop. Pressure drop in ductwork is inversely proportional to the fifth power of the duct diameter. For example, substituting a 16-in. duct for a 12-in. duct reduces pressure drop by about 75 percent.

Strategies for minimizing pressure drop include the use of lower-face-velocity air-handling units, low-pressure-drop filters, and optimally designed ductwork and air paths, including open plenums. Low-pressure-drop designs are applicable to all fan systems (e.g., recirculation, makeup, and exhaust). In addition to significant ongoing energy savings, low-pressure-drop systems enable the downsizing of fan motors, VFDs, and electrical-distribution systems, as well as quieter operation, more effective dehumidification, better filter effectiveness, and lower first cost (when downsized equipment and noise-abatement equipment are included in cost analyses).

Lower-pressure-drop filters often are an option in efforts to reduce energy costs. Larger filter surface area can reduce maintenance costs by allowing longer change intervals.

Air handlers are the greatest source of pressure drop because of the coils and filters they contain. A lower-face-velocity unit may result in first-cost savings and significantly reduced pressure drop.

Standard arguments against reducing face velocity beyond rules of thumb—

including the additional first costs associated with upsized fans, motors, drives, and silencers in a higher-pressure-drop system—usually are refuted by life-cycle-cost analysis.

OPTIMIZING AIR-CHANGE RATE

Air-change rate is the greatest determinant in recirculation-air-handling-system fan and motor sizing. Current recommendations, however, are not based on scientific findings. As a result, there is no clear consensus as to the optimum, and real-world operation varies widely (Figure 1).

For ISO Class 5 (Class 100) cleanrooms, 250 to 700 air changes per hour are recommended. Benchmarking studies, however, have shown that most facilities operate effectively at or below the low end of this range.

Reducing air-change rate yields energy savings (e.g., a 30-percent reduction in air-change rate reduces power consumption by 66 percent) and may improve cleanliness by minimizing turbulence. Reducing air-change rate also may allow the downsizing of fans, motors, etc. and corresponding first-cost savings.

Although the optimum may vary over time, typically, air-change rate is held constant. This presents another opportunity for savings, which the authors refer to as “demand-controlled filtration.” When a cleanroom is unoccupied, relatively few air changes per hour may be sufficient to maintain cleanliness.

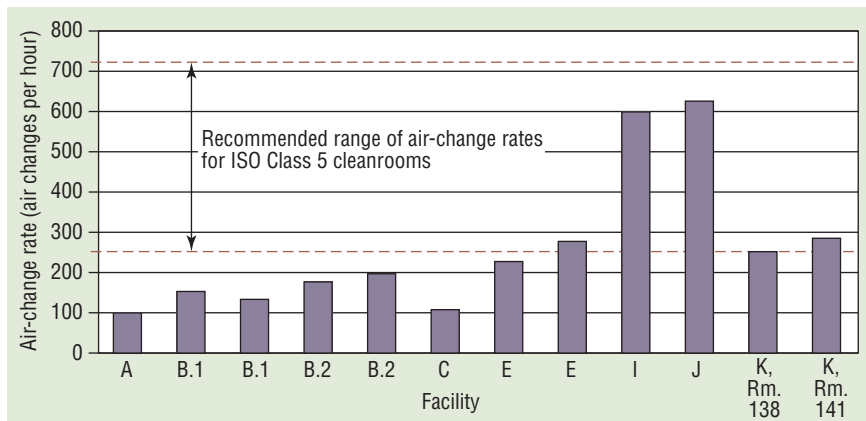


FIGURE 1. Measured air-change rates for ISO Class 5 (Class 100) cleanrooms.

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HEATING/PIPING/AIR CONDITIONING
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Airflow setback can be achieved manually, with timers, with occupancy sensors, or through real-time control by monitoring particle counts and varying airflow based on actual cleanliness. Studies in this area have been undertaken by International Sematech, the Massachusetts Institute of Technology, and Sandia National Laboratories. In a pilot test at Lawrence Berkeley National Laboratory (LBNL), the number of air changes per hour was reduced from 594 to 372 without particle counts increasing.

When demand-controlled filtration is employed, makeup-air and exhaust systems will continue to operate at their normal levels. System effects should be reviewed to ensure that desired pressurization levels can be achieved with any reduction in cleanroom airflow.

MAXIMIZING EXHAUST-SYSTEM EFFICIENCY

Exhaust systems are important targets in efforts to save energy, as they often operate continuously.

The first objective is to minimize total exhaust volume. This can be done through variable-flow control, process-equipment exhaust optimization, design approaches that maintain proper stack exit velocity with optimal bypass/dilution airflow, and elimination of pressure-drop bottlenecks in exhaust-ductwork systems.

Best-practice strategies include:

- Maintaining exit velocity by staging stacks or by other means.
- Manifolding exhaust streams when appropriate to maximize turndown capability.
- Using high-efficiency fan, motor, and drive components.
- Using variable-volume exhaust systems when feasible.
- Using bypass air to reduce the amount of conditioned air lost to exhaust.
- Increasing stack exit-nozzle area, which saves both conditioning and fan energy.
- Utilizing multiple stacks, possibly of different exit-nozzle areas. As exhaust volume drops, stacks can be shut off to reduce total operating nozzle area.
- Selecting low-pressure-drop scrubbers. Systems should be configured to operate redundant scrubbers in a parallel-flow, rather than staged, arrangement. The operation of two scrubbers at 50 percent of design flow results in a quarter of the pressure drop of operating a single scrubber at 100-percent flow.

OPTIMIZING EXHAUST

Conditioning cleanroom makeup air is expensive. Each cubic foot per minute of makeup air results in a cubic foot per minute of exhaust, which may require treatment before being released.

The suggested exhaust quantities of many equipment manufacturers are based on rules of thumb and, thus, are

prone to being overstated. Typically, a crude face-velocity approach is used to estimate exhaust rates required for containment. Good practice suggests using direct measurements of containment to set exhaust rates.

In a study by International Sematech, a combined exhaust-airflow reduction of 28 percent (2,994 cfm to 2,146 scfm) was attained for four classes of semiconductor process tools: wet benches, gas cabinets, ion implanters, and vertical furnaces. At a typical semiconductor facility, such a reduction could amount to savings of more than \$33,000 a year.

USING MINIENVIRONMENTS

Minienvironments allow better contamination control and process integration through better control of pressure differences or the use of unidirectional airflows.

Minienvironments utilize fan-filter units, the efficiencies of which can vary greatly. In case studies, fan energy ranged from 26 to 32 w per square foot in ISO Class 4 minienvironments and from 10 to 38 w per square foot in a typical cleanroom. Because minienvironments have a far smaller footprint than the cleanroom in which they are placed, overall energy use can decline considerably, if the cleanroom conditions can be relaxed.

Simply adding minienvironments to a cleanroom will increase airflow-delivery power density and energy intensity. Energy savings occur when cleanliness is optimized and minienvironments are integrated with the surrounding space.

OPTIMIZING RECIRCULATION-AIR SYSTEMS

Recirculation-air-handler fan energy can account for 10 to 30 percent of total cleanroom energy use. LBNL measured the performance of fan-filter-unit, ducted-HEPA, and pressurized-plenum designs, finding that pressurized-plenum designs tend to be the most efficient (Figure 2), despite a large variation in efficiency (Figure 3). All system configurations

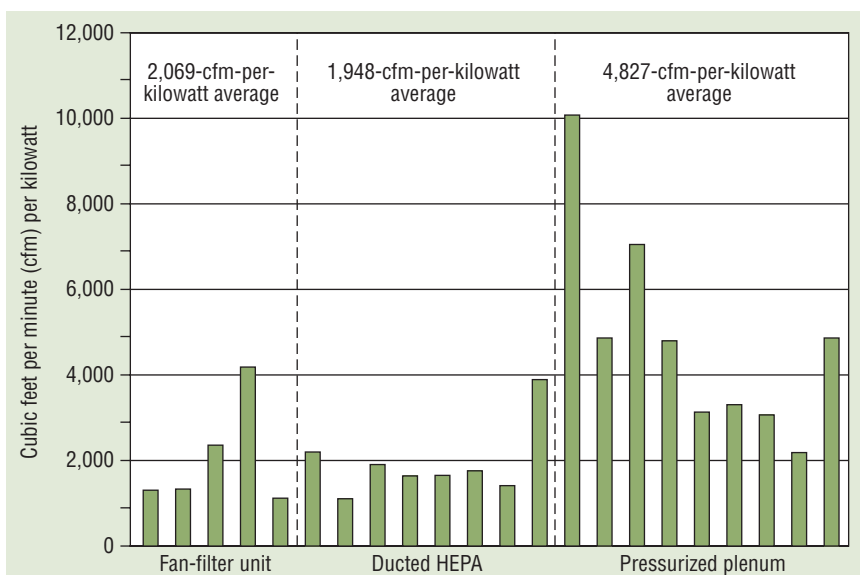


FIGURE 2. Recirculation-air-handling performance for ISO Class 4 through ISO Class 7 cleanrooms. Note: Higher is better.

demonstrated large energy savings from low-pressure-drop design.

Efficiency strategies documented in other best-practice summaries are applicable to any recirculation configuration.

At one benchmarked site in the LBNL study (Facility C), a very high efficiency (10,140 cfm per kilowatt) was measured. This was achieved through the use of multiple large-diameter axial vane fans

controlled by VFDs with a low-pressure-drop design.

Notably, the best fan-filter-unit arrangement, which utilized a plenum return with integrated low-face-velocity sensible-cooling coils, performed better than some of the pressurized-plenum cleanrooms. Through careful design, a two- to fourfold improvement in fan-filter-unit efficiency can be realized.

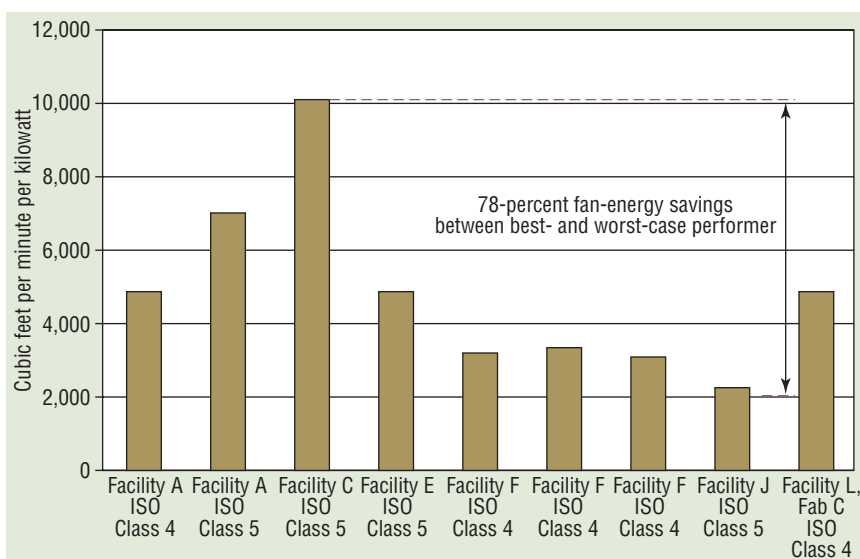


FIGURE 3. Pressurized-plenum recirculation-air-handling performance. The total recirculation-fan-system operating pressure drop at Facility J was 1.9 in. wg, compared with 0.45 in. wg at Facility C.

The overall air-delivery efficiency of fan-filter-unit systems is significantly higher when sensible-cooling devices are integrated into an air-recirculation system than when separate sensible-cooling devices requiring additional fans to deliver cooled air as part of air recirculation are used.

OPTIMIZING THE USE OF CHILLER SYSTEMS AND COOLING TOWERS

Chiller energy can represent 10 to 20 percent of total cleanroom energy use. Chillers with variable-speed drives (VSDs) generally operate more efficiently at part load and are more responsive to varying loads than constant-speed-drive chillers with throttling or staging load controls. Other potential benefits of chillers with VSDs are capital savings, lower noise levels, reduced compressor wear, better electrical protection, improved power factors, and reduced harmonics.

Temperature reset also provides substantial savings opportunities. Chiller work is proportional to compressor vapor-pressure work. This work can be reduced if chilled-water temperature is raised and/or condenser-water temperature is lowered. For centrifugal-compressor-based chillers, a 1-F change in chilled-water-supply temperature can increase efficiency by 1 to 2 percent. The temperature can be reset based on outside-air temperature.

In one benchmarked project, medium-temperature chillers were approximately 14-percent more efficient because of a chilled-water-temperature difference of only 6 F.

In many cleanrooms, chilled-water requirements are best served by medium-temperature (55 to 70 F) chilled water. Because of less compressor work, medium-temperature chillers have smaller compressors, which lower equipment first cost, as well as the cost of electrical infrastructure.

Cleanroom facilities typically need low-temperature water only to handle peak loads, while chillers operate most

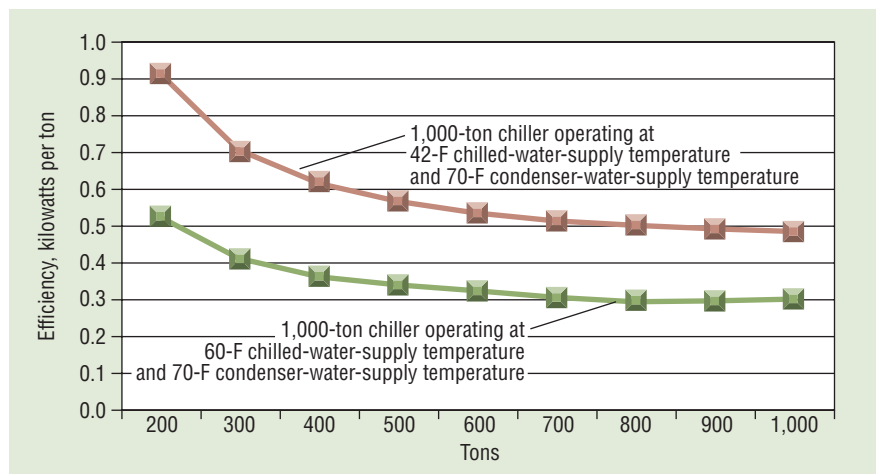


FIGURE 4. Comparison of low- and medium-temperature water-cooled chillers.

efficiently when temperature lift (the difference between evaporator and condenser temperature) is minimized. Peak loads occur 2 to 5 percent of the time over the course of a year.

As shown in Figure 4, the energy savings of a chiller operating at 42 F, rather than 60 F, are 40 percent over the entire load range. In well-configured and controlled systems, there also are first-cost savings for condenser pumps and cooling-tower savings because the more-efficient chiller has less total heat to reject.

In a pilot project for a multiple-cleanroom-building campus, the implementation of a dual-temperature chilled-water system was analyzed. The site had 2,370 tons of makeup-air cooling and 1,530 tons of sensible and process cooling. With 42-F water for low-temperature use and 55-F water for medium-temperature use, approximately \$1 million was saved per year, with a payback of two years.

WATER-SIDE FREE COOLING

A medium-temperature loop greatly expands the potential for free cooling, or the utilization of a cooling tower for chilled-water production. Chilled-water systems use chillers that typically operate at 0.5 to 0.7 kw per ton. The authors' benchmarked sites, however, showed cooling-tower efficiencies ranging

from 0.013 to 0.19 kw per ton (i.e., 90-percent lower in many cases). A low approach temperature on a tower is critical to maximizing energy savings.

Free cooling utilizes a cooling tower's evaporative-cooling capacity to indirectly produce chilled water for use in medium-temperature applications, such as process- and sensible-cooling loops. Free cooling is best suited for climates with wet-bulb temperatures below 55 F for 3,000 or more hours a year. It is applied most effectively to serve process- and/or sensible-cooling loops requiring 50- to 70-F chilled water. Under this approach, a traditional chiller is used to provide cooling during hot periods and always is available as an emergency backup.

Chilled-water reset plays an integral role in the optimization of free cooling by increasing the chilled-water-supply set point during mild conditions, when lower-temperature chilled water is not required to meet cooling needs and cooling towers are able to produce the lowest-temperature free-cooling water. A VSD should be used for the fan motor to minimize on-off cycling and maximize energy savings.

One benchmarked facility had 900 tons of installed cooling capacity, but was operating at 561 tons. A heat exchanger used to isolate condenser water from the process-cooling loop

yielded annual savings of 1,140 mwh and a simple payback of 1.2 years.

VARIABLE-SPEED PUMPING

At one benchmarked site, the water pumps accounted for 17 percent of total energy use. Targets for variable-speed control include hot-water pumps, chillers, primary-loop chilled-water pumps, secondary-loop chilled-water pumps, condenser-water pumps, and cooling-tower fans.

VSD pumps should be used to control and balance water flows to minimize the need for throttling design. For example, they should be used to avoid or minimize the use of booster pumps and close bypasses, which, though common in practice, are not energy-efficient.

The observed best practice in overall water-pump efficiency is:

- Primary chilled-water pumps: 0.047 kw per ton.
- Secondary chilled-water pumps: 0.019 kw per ton.
- Condenser water pumps: 0.089 kw per ton.

The authors' benchmarking identified overall pumping efficiencies of 0.13 to 0.44 kw per ton.

OPTIMIZING VACUUM PUMPS

Many of the process technologies within cleanrooms offer energy-saving opportunities. For example, vacuum pumps typically account for 5 to 10 percent of a semiconductor cleanroom facility's total electricity consumption. Recent advances have improved the efficiency of vacuum pumps by 50 to 60 percent. Through integration of the pumps with process controls, further savings are possible via implementation of an idle mode when vacuum is not needed. Combining best-practice technology and design, such as placing vacuum pumps close to supported equipment, makes 50- to 90-percent reductions in vacuum-pump energy use possible. Further benefits include up

to 65-percent less noise, downsized electrical infrastructure, and downsized central cooling equipment.

Variable-speed capability in standby mode is being integrated into the design of some high-efficiency dry-vacuum pumps. To implement idle-mode operation, process equipment is being enabled to send an idle signal to vacuum pumps.

In benchmarking studies of six dry-vacuum pumps serving a semiconductor



Ducted HEPA filters serving a cleanroom.

wafer-etch process, chambers in the process oscillated between "on" and "off" every two minutes. The facility had a total of 300 such pumps in use, at an average power demand of 3 kw. The savings potential of eliminating the on/off cycling is \$394,000 per year, which would free up 125 tons of cooling, worth in excess of \$100,000.

PULLING IT ALL TOGETHER

Following best practices is not just a matter of substituting better technologies and operational procedures. Design and decision-making also must be addressed. This entails:

- Integrating energy management with functions such as risk management, cost control, quality assurance, employee recognition, and training and using life-cycle-cost analysis as a decision-making tool.

• Creating design-intent documents to involve all key stakeholders, keeping the team "on the same page," and clarifying and preserving the rationale for key design decisions.

• Adopting quantifiable goals based on best practices.

• Introducing energy optimization at the earliest phase of design to minimize construction and operating costs, avoiding excessive/redundant "safety margins," and right-sizing to trim first costs.

• Including integrated monitoring, measuring, and controls in facility design.

• Benchmarking existing facilities, tracking performance, and assessing opportunities.

• Incorporating a comprehensive commissioning (quality-assurance) process into new-construction and retrofit projects.

• Including periodic "recommissioning" in overall facility-maintenance programs.

• Evaluating the potential for on-site power generation, including combined-heat-and-power technologies.

• Ensuring that all members of the facility-operations staff receive site-specific training that includes identification and proper operation of energy-efficiency features.

NOTE

1) The research reported in this article was performed by Lawrence Berkeley National Laboratory and Rumsey Engineering for the California Energy Commission's Public Interest Energy Research (PIER) program. For more information, visit hightech.lbl.gov.

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