LBNL-4848E

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Cleanroom Energy Efficiency: Metrics and Benchmarking

Paul Mathew, William Tschudi, Dale Sartor

Lawrence Berkeley National Laboratory

James Beasley

International SEMATECH Manufacturing Initiative

October 2010

Published in
ASHRAE Journal, v. 53, issue 10

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.

Cleanroom Energy Efficiency: Metrics and Benchmarks

Paul A. Mathew, Ph.D, William Tschudi, P.E, Dale Sartor, P.E.
Lawrence Berkeley National Laboratory

James Beasley, LEED AP
International SEMATECH Manufacturing Initiative

1 Introduction

Cleanrooms are among the most energy-intensive types of facilities. This is primarily due to the cleanliness requirements that result in high airflow rates and system static pressures, as well as process requirements that result in high cooling loads. Various studies have shown that there is a wide range of cleanroom energy efficiencies and that facility managers may not be aware of how energy efficient their cleanroom facility can be relative to other cleanroom facilities with the same cleanliness requirements [1,2]. Metrics and benchmarks are an effective way to compare one facility to another and to track the performance of a given facility over time [3].

This article presents the key metrics and benchmarks that facility managers can use to assess, track, and manage their cleanroom energy efficiency or to set energy efficiency targets for new construction. These include system-level metrics such as air change rates, air handling W/cfm, and filter pressure drops. Operational data are presented from over 20 different cleanrooms that were benchmarked with these metrics and that are part of the cleanroom benchmark dataset maintained by Lawrence Berkeley National Laboratory (LBNL) [4,5]. Overall production efficiency metrics for cleanrooms in 28 semiconductor manufacturing facilities in the United States and recorded in the Fabs21 database are also presented.

2 Environmental Condition Metrics

The first opportunity to reduce cleanroom energy use is to ensure that environmental operating parameters are optimized to the actual process requirements within the cleanroom, and ensure they are not unnecessarily stringent. The cleanroom environmental conditions most often controlled include space pressurization, temperature, and relative humidity.

2.1 Space Pressurization

This metric describes the pressure differential between the cleanroom and the surrounding spaces. Excessive pressurization increases fan static pressure requirements and energy use. Optimizing the space pressure differential to the minimum required to meet cleanliness classification requirements will ensure the required fan static pressure from space pressurization will be at a minimum value and have a lower energy usage. Figure 1 shows that space pressurization in the benchmark dataset varies from 0.05 to 0.14 in. w.g. [12 to 35 Pa]. In facilities with multiple clean spaces, the architectural layout of the spaces can be optimized to limit the pressure differential cascade.

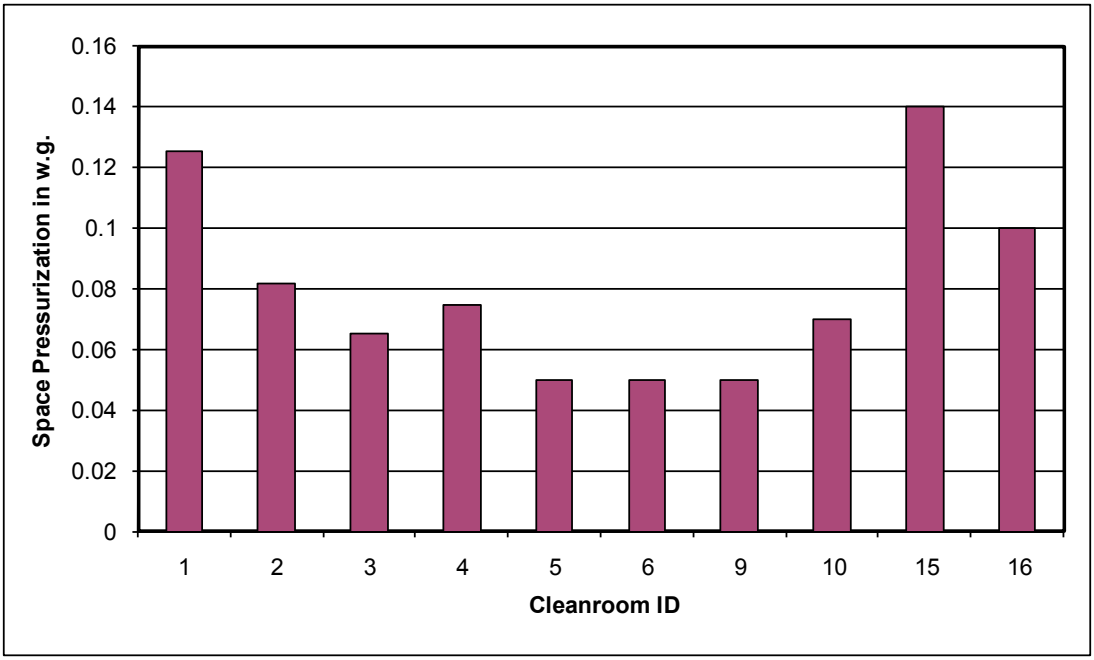

Figure 1. Space pressurization values in the LBNL benchmark dataset

2.2 Space Temperature and Humidity

Maintaining narrow operating ranges for space temperature and relative humidity usually requires substantial energy use to cool, reheat, and humidify the supply air flow. Allowing wider operating ranges for space temperature and relative humidity can reduce energy use. If an existing cleanroom has a narrow operating range for space temperature and relative humidity, the cleanroom operators should carefully review whether the current processes legitimately require these narrow operating ranges. Figures 2 and 3 show a wide range of space temperature and relative humidity in the benchmark dataset. In some facilities, the measured space temperatures were up to 5 F [2.7C] below design values. The relative humidity operating ranges were generally between 5 and 10% of setpoint.

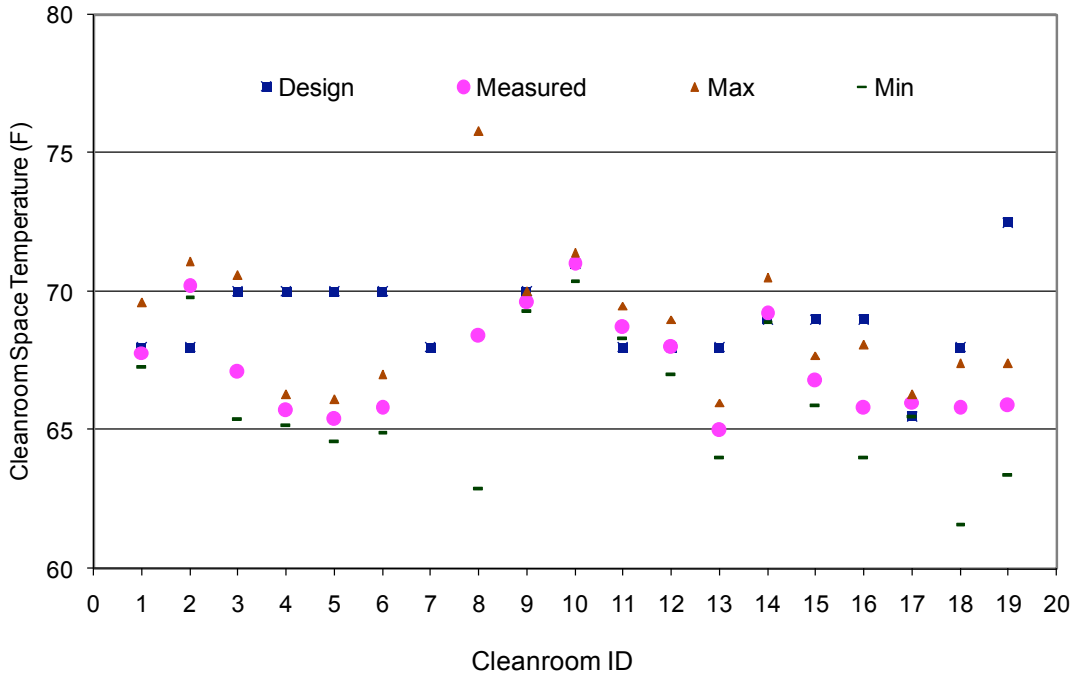

Figure 2. Design and measured temperatures in the LBNL benchmark database

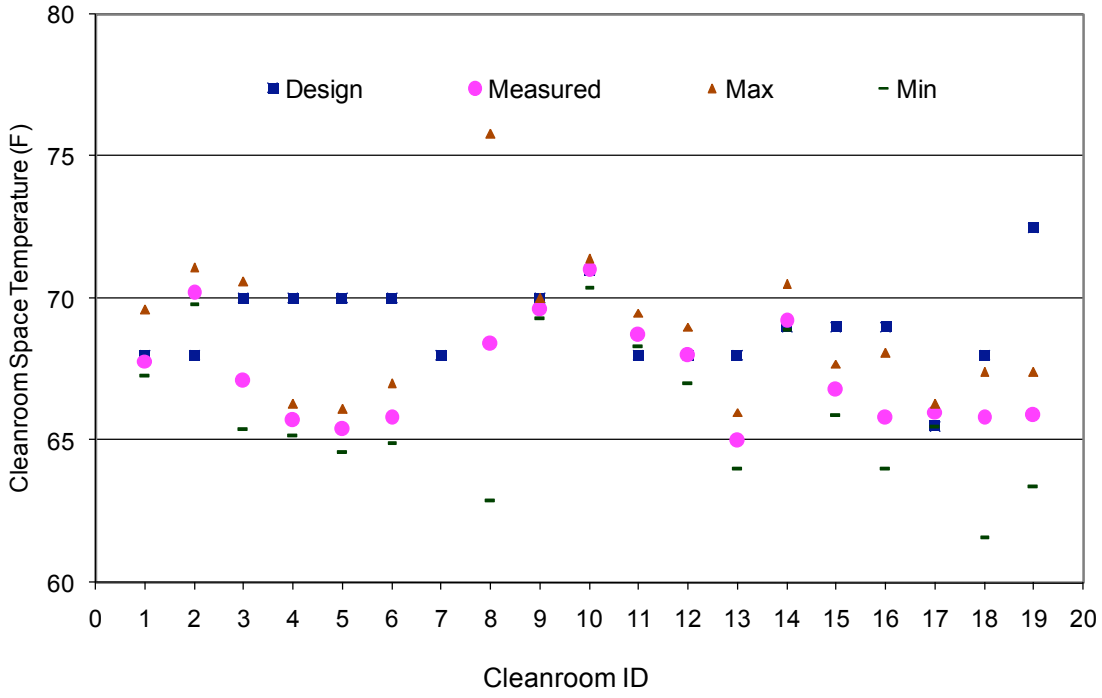

Figure 3. Design and measured relative humidity in the LBNL benchmark database

3 Airflow System Metrics

3.1 Recirculation Air Change Rates

This metric deals with the cleanroom recirculation air changes per hour (ACH). Figure 4 shows the air change rates for ISO class 5 cleanrooms in the benchmark dataset. Cleanroom air change rates should be optimized to meet the cleanliness level and should not be higher than required to meet particulate requirements during operating mode. The benchmark data shows that air change rates vary significantly among different cleanrooms having the same cleanliness classification. The ACH needed depends largely on the amount of contamination, which is not necessarily well understood at design. Thus if a designer was too conservative, the cleanroom may be operating at 500 ACH when 300 ACH may be adequate to meet cleanliness requirements. Benchmarking ACH is a first step in helping to identify a potential efficiency opportunity. Demand-controlled ventilation (i.e., modulating air change based on monitoring particle counts) is one way to optimize the recirculation air change rates in lieu of pressurization-based control. However, if there are code requirements, minimum flows will have to be maintained while varying the airflow.

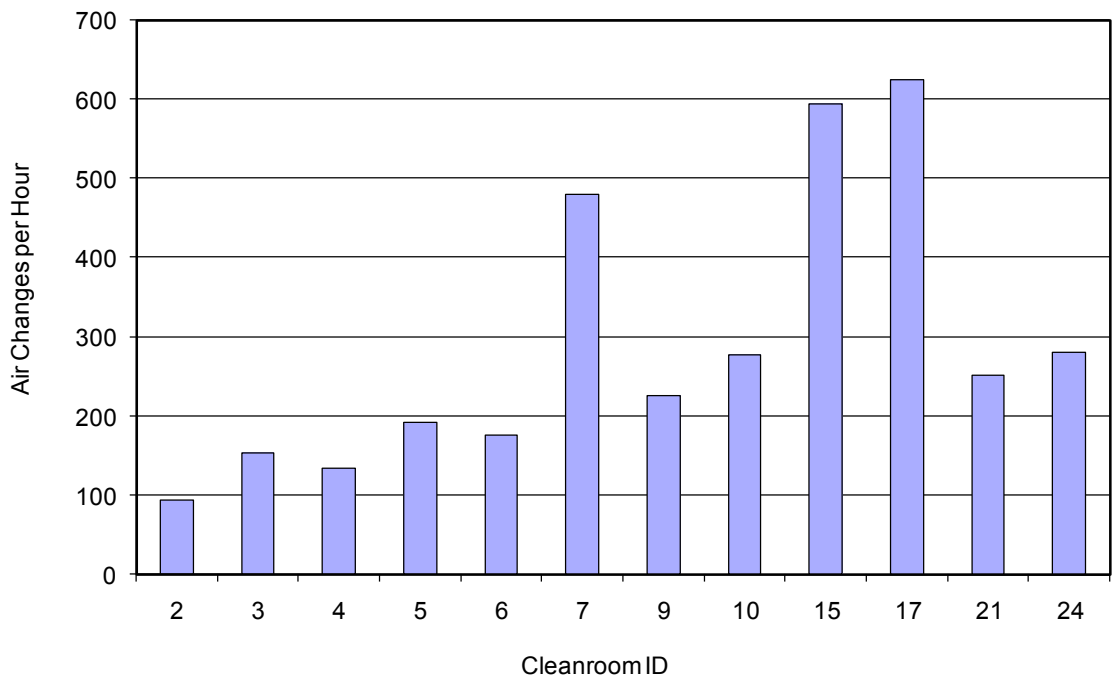

Figure 4. Air change rates in for various ISO-Class-5 cleanrooms in the LBNL benchmark database. ISO-Class-5 is equivalent to class 100 in FS 209

3.2 Air Handling System Airflow Efficiency

This metric deals with the overall airflow efficiency of air handling systems in terms of the total fan power required per cubic foot per minute (CFM) of airflow. It provides an overall measure of how efficiently air is moved through the cleanroom mechanical systems. Air flow efficiency can be analyzed separately for the recirculation units (RCU), make-up air units (MAU), as well as air exhaust systems. As shown in Figures 5 and 6, the benchmark dataset shows a wide airflow efficiency range. The RCU benchmark data showed that the average airflow efficiency was 0.43

W/cfm [0.91 W/L.s^{-1}] for pressurized supply air plenum systems as compared to 0.63 W/cfm [1.34 W/L.s^{-1}] for fan-filter units. Several actions can be taken to improve airflow efficiency:

- Reduce system pressure drop by removing or changing components (e.g., removing excessive filters, changing dirty filters, using lower pressure drop filters).
- Improve fan system efficiency by retrofitting motors, belts, and drives.
- Selecting efficient fan-filter units matching the pressure conditions.
- Designing new systems to include efficient variable speed fans, low pressure drop filters, and low pressure drop ducting and supply air plenums.

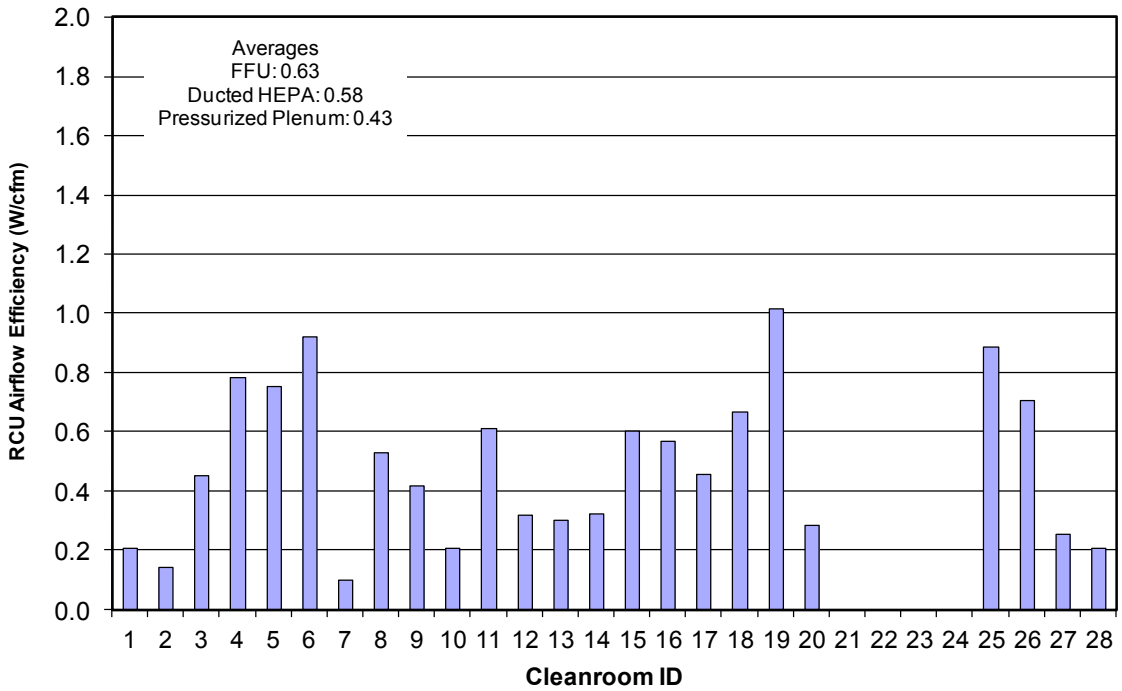

Figure 5. RCU airflow efficiency for cleanrooms in the LBNL database

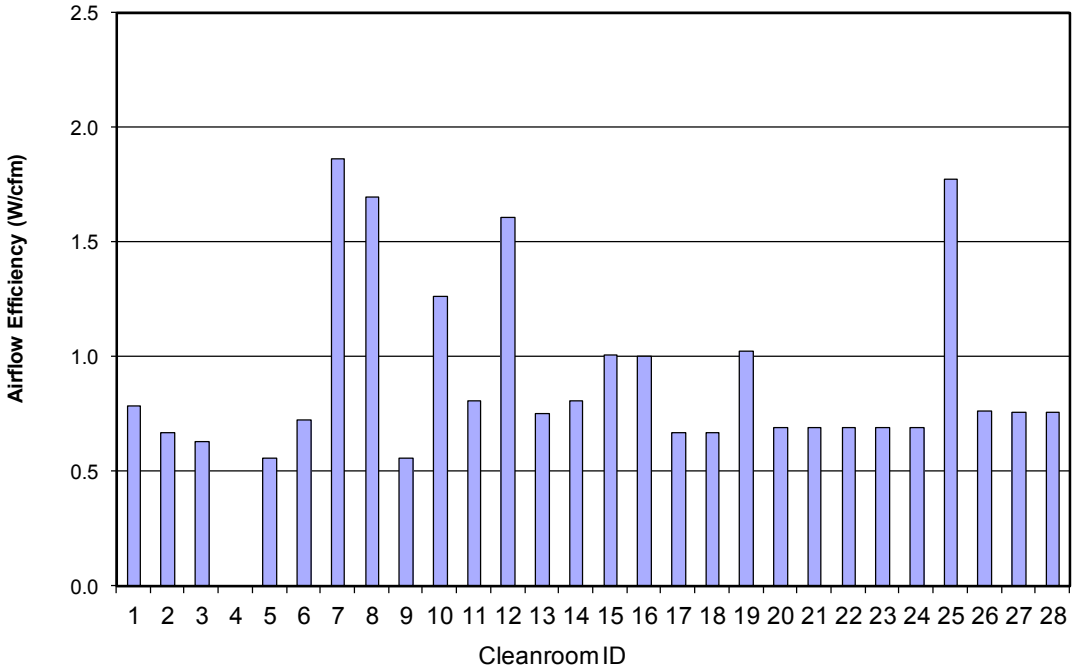

Figure 6. MAU airflow efficiency for cleanrooms in the LBNL database

Figure 7 shows the relationship between RCU airflow efficiency and ceiling HEPA filter exiting air velocity. Similarly, Figure 8 shows the relationship between RCU airflow efficiency and ceiling filter coverage. Although ceiling filter exit velocity and filter coverage can influence the airflow efficiency, the data suggest that there is not necessarily a strong correlation between airflow efficiency and either ceiling filter exit air velocity or ceiling filter coverage. As the next section shows, filter pressure drop is more critical.

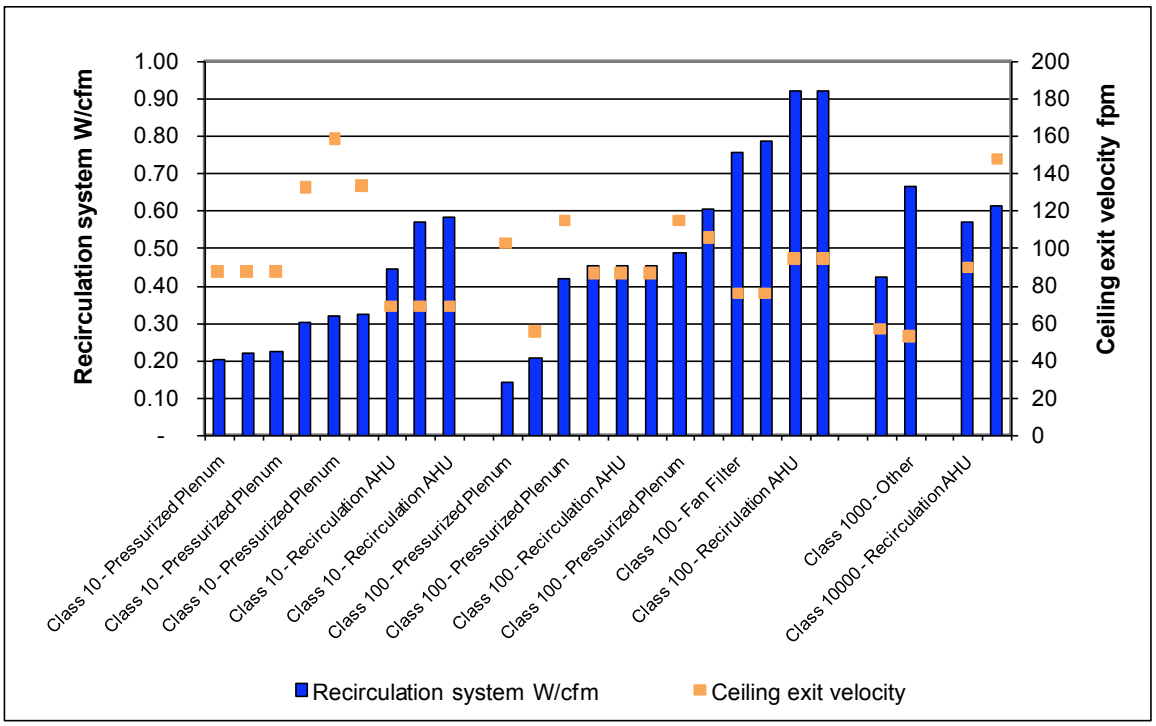

Figure 7. Relationship between recirculation system W/cfm and ceiling filter exit velocity

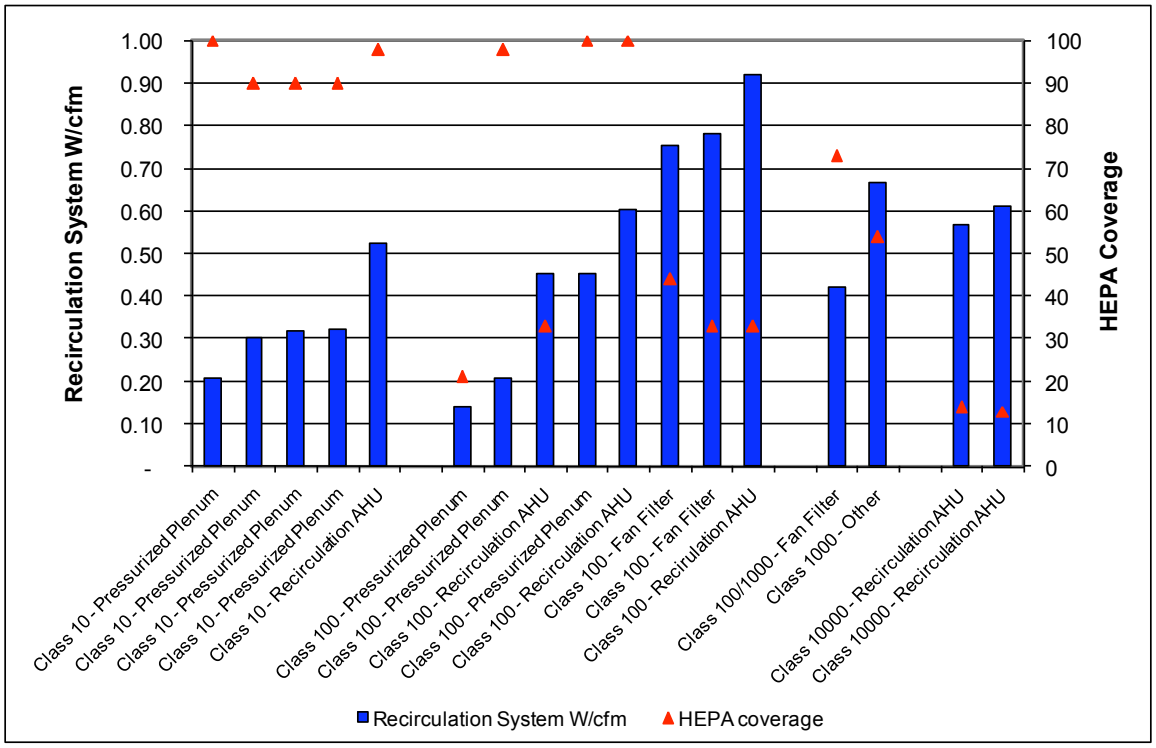

Figure 8. Relationship between recirculation system efficiency and filter coverage

3.3 HEPA Filter Pressure Drop

This metric deals with the pressure drop across the filters in the RCUs or MAUs. The benchmark data show a high variation within a given cleanliness class (figures 9 and 10). Figure 11 shows a

strong relationship between filter pressure drop and RCU airflow efficiency. Low pressure drop filters can play a significant role in reducing energy use of RCUs. Similarly, increasing filter coverage could lower overall system pressure drop for ducted or plenum systems.

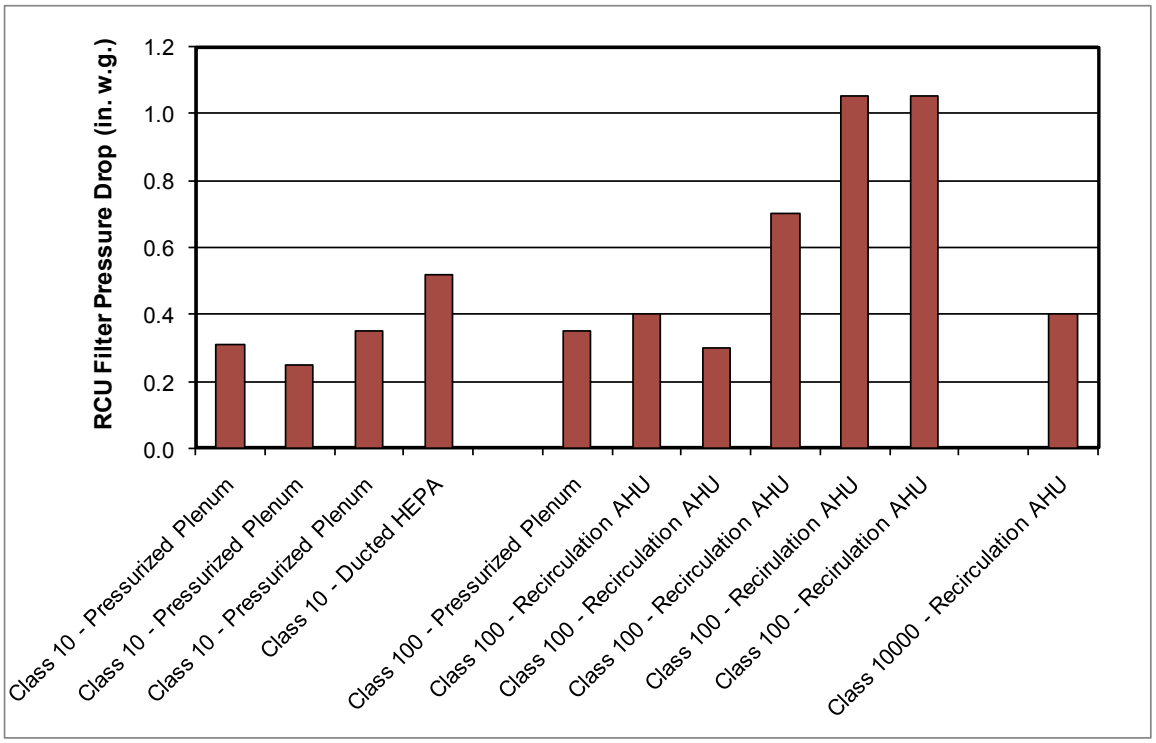

Figure 9. RCU filter pressure drop for cleanroom RCUs in the LBNL database.

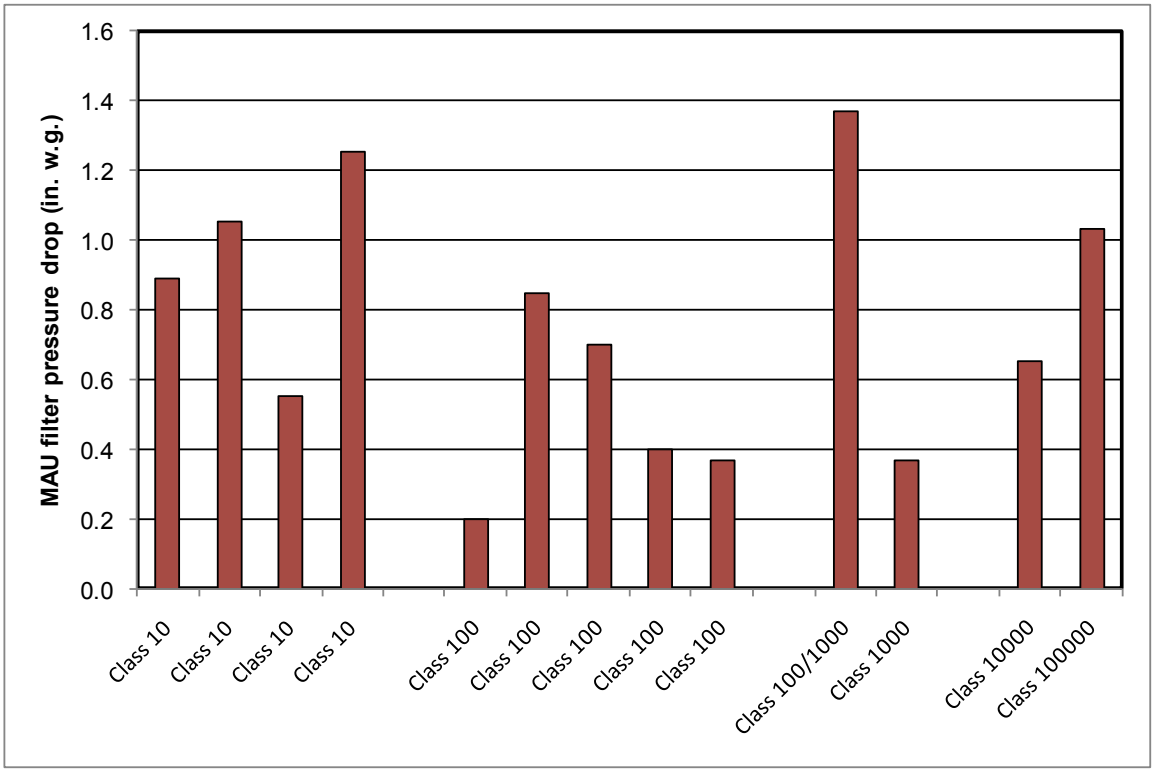

Figure 10. MAU filter pressure drop for cleanroom MAUs in the LBNL database.

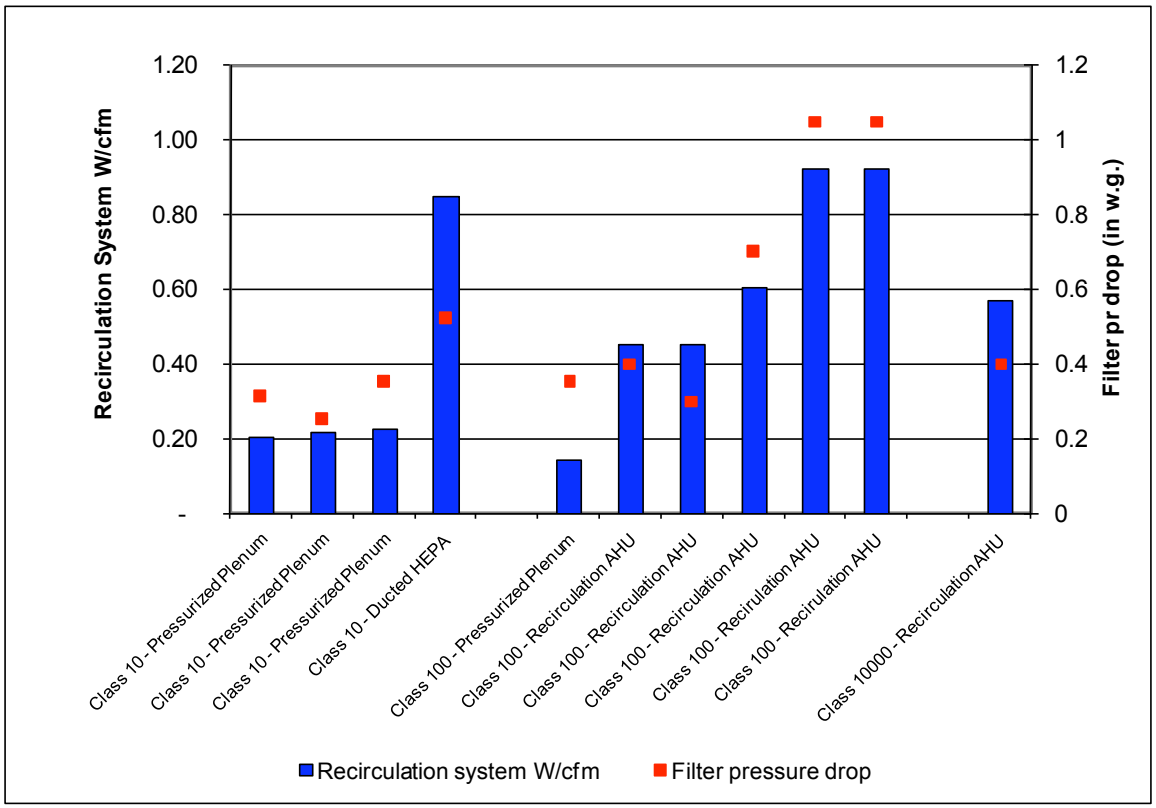

Figure 11. Relationship between RCU W/cfm and filter pressure drop.

4 Heating and Cooling System Metrics

The key metrics and benchmarks to evaluate the efficiency of chiller and boiler systems serving cleanrooms are no different than those typically used in other commercial or industrial buildings. These include chiller plant efficiency (kW/ton), installed capacity vs. actual peak load, boiler efficiency (%), pumping efficiency (hp/gpm, $W/L.s^{-1}$), etc. Since these are well-documented elsewhere, they are not discussed here. However, one key metric which is often overlooked is the amount of reheat energy. Cleanroom reheat energy usage can be significant when the required space temperature and relative humidity requirements are very stringent, space cooling load has wide fluctuations, or if controls are poorly calibrated or lack integration (e.g. independent RCU and MAU controls). While there is no well-established metric for assessing reheat energy use, we suggest a metric such as reheat energy use factor, defined as the ratio of the reheat energy use to the total heating energy use. A best practice benchmark for this would be 0% (i.e. complete elimination of reheat energy use for temperature control).

5 Overall Measures of Energy Productivity – Semiconductor Facilities

Generally, facility-level energy use metrics (such as BTU/sf or kWh/sq.m) are the most common means of comparing the overall facility energy usage intensity. However, such metrics are usually not effective for comparing cleanrooms, because cleanroom energy use is typically driven by the process loads, which vary widely across different cleanrooms. If the processes within the cleanroom can be quantified as a metric, obtaining an overall measure of energy efficiency for the cleanroom per unit of process is possible.

For example, semiconductor fabrication facilities have two primary units of output: the sq.cm of silicon wafers and the sq.cm of wafers multiplied by the number of mask layers applied on each wafer. Both of these metrics can be used to normalize the total energy use of the facility, yielding two overall measures of energy productivity: BTU/sq.cm [kWh/sq.cm] of wafer outs and BTU/sq.cm of wafer outs x mask layers. Figures 12 and 13 show the value of these metrics for 28 U.S. fabrication facilities that are recorded in the Fabs21 benchmarking tool [6]. The data show a wide range of efficiency. Even when normalizing for mask layers (Figure 13), the most efficient facility is almost six times more efficient than the least efficient facility.

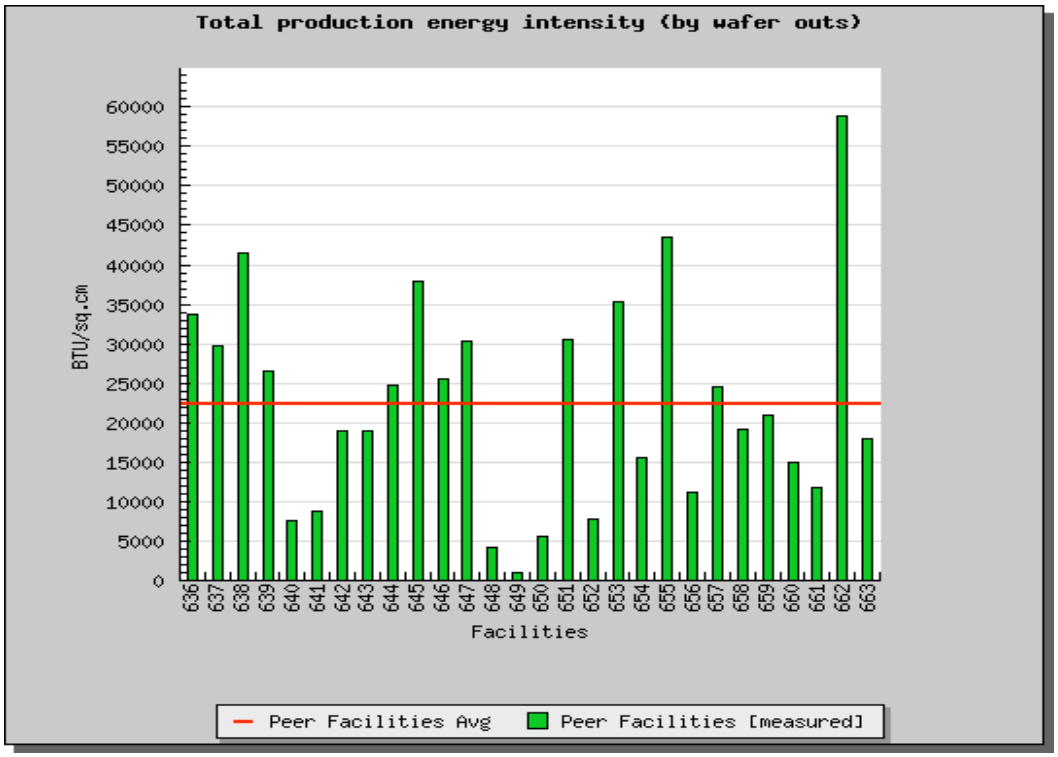

Figure 12. Production energy intensity (by wafer outs) for semiconductor fabrication facilities in the Fabs21 database

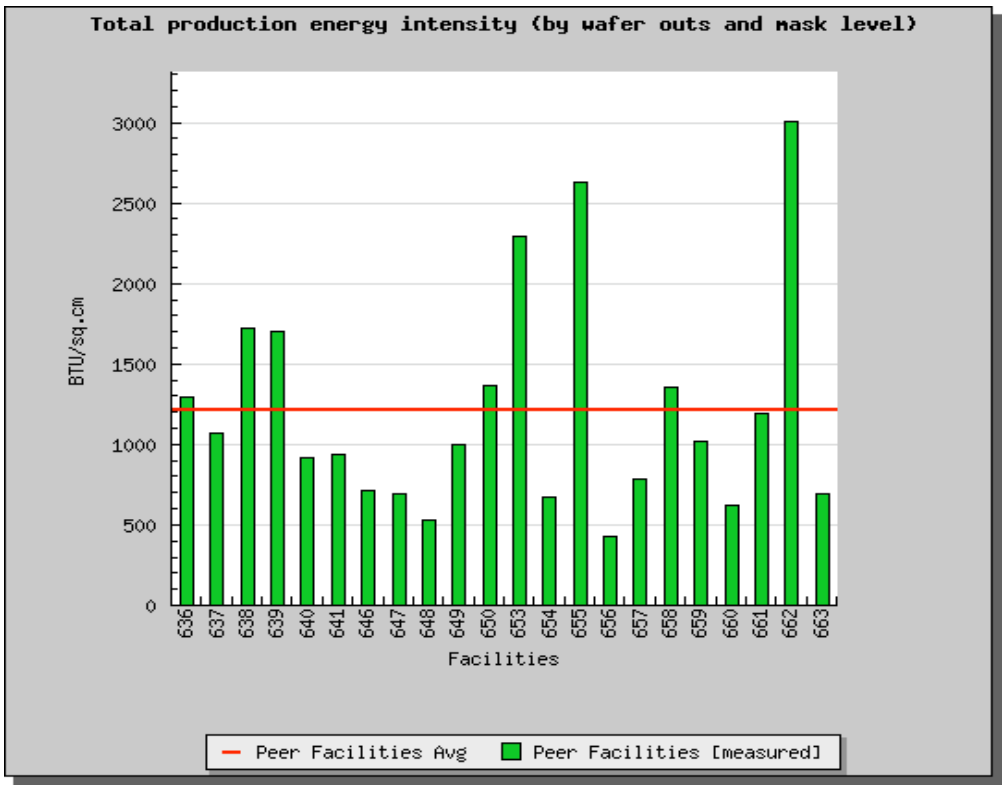

Figure 13. Production energy intensity (by wafer outs and mask level) for semiconductor fabrication facilities in the Fabs21 database

6 Conclusion

Cleanroom operators are much more likely to meet energy efficiency goals if quantitative metrics and targets are explicitly identified and tracked. Environmental metrics such as space pressurization, temperature and relative humidity setpoints should not be more stringent than what is actually required for the process or people comfort. The key airflow system metrics include RCU and MAU system airflow efficiency (W/cfm, $W/L.s^{-1}$) and RCU and MAU filter pressure drops. Heating and cooling system efficiency metrics for cleanrooms are not significantly different from those used for other commercial or industrial buildings. Facility-level overall energy productivity metrics can be developed for certain types of cleanrooms, if there is an output measure that can be used to normalize energy use. This article presented productivity metrics for semiconductor fabrication facilities, in which energy use can be normalized by wafer outs and mask layers.

Metrics and benchmarks are in effect key performance indicators for the quality of design, construction and operation. To ensure that they are effectively used, cleanroom operators and designers should obtain the buy-in of all the key stakeholders, incorporate them into programming documents, and track them consistently.

Acknowledgements

This work was supported by the New York State Energy Research and Development Authority, California Energy Commission, and by the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231. This article was based on a self-benchmarking guide developed for the New York State Energy Research and Development Authority (NYSERDA) and previous benchmarking studies supported by the California Energy Commission (CEC). The Fabs21 database was developed for the International SEMATECH Manufacturing Initiative (ISMI).

References

1. Tschudi, W., K. Benschine, S. Fok, and P. Rumsey. 2001. "Cleanroom Energy Benchmarking in High-Tech and Biotech Industries." Proceedings of the 2001 ACEEE Industrial Conference.

2. Xu, T. and W. Tschudi. 2002. "Energy Performance of Cleanroom Environmental Systems." Proceedings of the 48th Annual Technical Meeting and Exposition of the Institute of Environmental Science and Technology (ESTECH), April 28-May 1, 2002, Anaheim, CA. Lawrence Berkeley National Laboratory Report No. LBNL-49106.

3. Darby, S. The Effectiveness Of Feedback On Energy Consumption, Environmental Change Institute, University of Oxford, April 2006, http://www.eci.ox.ac.uk/research/energy/downloads/smart-metering-report.pdf

4. Tschudi, W. F. and P. Rumsey. 2004. "Using Benchmarking to Identify Energy Efficiency Opportunities in Cleanrooms: The Labs21 Approach." ASHRAE Symposium.

5. Clean room self-benchmarking guide: http://hightech.lbl.gov/benchmarking-guides/clean.html

6. Fabs21 database of energy efficiency for semi-conductor manufacturing facilities: http://fabs21.lbl.gov/