Worldwide Fab Energy Survey Report

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Worldwide Fab Energy Survey Report

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REPORT SUMMARY

The international semiconductor industry has worked consistently to reduce the following:

- The amount of energy used by semiconductor manufacturing facilities (fabs) to minimize pollutants
- The industry's effect on global warming
- Costs

As part of that effort, EPRI and SEMATECH launched an international benchmarking study to collect data about energy consumption from facilities around the world. The data collected can be used to improve processes and systems industry-wide.

Background

The U.S. semiconductor industry has called for reducing energy used in semiconductor manufacturing processes. Although most semiconductor manufacturers have identified and implemented energy efficiency measures in their fabs, the lack of standardized energy consumption data within the semiconductor industry makes reliable comparison of energy efficiency among diverse fabs difficult.

This study is a collaborative effort between International SEMATECH member companies and several non-member companies. In all, 14 fabs worldwide agreed to participate by collecting and sharing data on energy consumption.

Objectives

The following are the three main objectives of this study:

- Identify (for the sake of comparison) energy and utility consumption levels for (1) overall fab use, (2) facility systems and subsystems, and (3) process tools.
- Identify opportunities for energy reduction in participants' facilities.
- Identify the relationship between design parameters and actual tool energy use in fabs to develop a baseline for comparison with next generation process tools.

This report is designed to help facility managers and engineers better understand energy flows and consumption levels within fabs and ultimately to identify opportunities for energy conservation measures.

Approach

Energy consumption levels were studied in 14 fabs in such countries as the United States, Korea, Singapore, Taiwan, France, and the Netherlands. More than 1,200 records from the participating fabs were analyzed. In addition, baseline energy consumption data was generated for fab facility systems, process areas, and process tools. Surveys were conducted according to a detailed methodology.

Comparisons of energy use among diverse fabs were facilitated by using a new metric introduced in this study—kilowatt-hours (kWh) per unit of production (in which “unit of production” is defined as the square inches of wafer processed per year multiplied by the average number of mask layers per wafer processed). This metric provides a new means for quantifying energy efficiency while normalizing for variations in both the production capacity of different fabs and the manufacturing complexity of their products.

Results

On average, the fabs in this study consumed 7.45 $kWh/inch^2$ (1.15 kWh/cm^2) of wafer processed and 0.393 kWh of electrical energy per unit of production. These figures are consistent with the level of energy efficiency being achieved industry-wide. When compared to each other, the most energy-efficient fabs overall tended to be newer fabs, minienvironment fabs, fabs with extensive monitoring systems, and fabs that had implemented aggressive programs to minimize exfiltration. In addition, fab systems that were equipped with high efficiency motors and variable speed drives tended to be among the top performers in each facility system.

The largest category of electrical energy consumption in the fabs studied was process tools, which consumed over 40 percent of the electrical energy used by the fabs. The next highest energy-consuming facilities systems were the chillers and recirculating air units, which respectively consumed about 25 percent and 11 percent of all the electrical energy used. The analysis of process tool energy used revealed significant electrical energy use in the thin films, dry etch, thermal, and patterning process areas.

EPRI Perspective

EPRI’s Center for Electronics Manufacturing (CEM) was created to help member utilities address the energy and water needs of semiconductor manufacturers. The semiconductor industry is committed to improving the energy and water use efficiency of their manufacturing processes without sacrificing productivity and quality. This benchmarking study is part of effort to identify and share best practices worldwide. In addition, the study represents a first step toward enabling future analyses and comparisons of fab energy efficiency.

Key Words

Power Consumption
Energy Use
Facilities
Semiconductor Equipment
Nitrogen
Ultrapure Water
HVAC
Exhaust

ABSTRACT

This report includes revised unit of production data in Appendix G. The report describes a study of energy consumption levels in 14 semiconductor fabs in the United States, Korea, Singapore, Taiwan, France, and the Netherlands. The report details metrics selection, data collection, reporting, and analysis of more than 1,200 records from the participating fabs and presents baseline data on energy consumption levels for fab facility systems, process areas, and process tools. In the analysis of the data, fab energy use was allocated among eight facilities systems—central plant, makeup air, recirculating air, exhaust, nitrogen, compressed dry air, process cooling water, and ultrapure water (UPW)—and process tools. The use of electrical energy, process cooling water, UPW, and exhaust by process tools was further allocated among six key process areas (patterning, thermal, thin films, dry etch, ion implant, and wafer cleaning).

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ACRONYMS

AHU	Air handling unit
AMHS	Automated materials handling system
BTU	British thermal unit
C	Celsius
CDA	Compressed dry air
cfm	Cubic feet per minute
CHW	Chilled water
cmh	Cubic meters per hour
cmm	Cubic meters per minute
CMP	Chemical mechanical polish
CMS	Cubic meters per second
CVD	Chemical vapor deposition
DI	Deionized water
DTM	Designed-to-measured ratio
ECM	Energy conservation measure
EPI	Epitaxy
ESH	Environment, safety, and health
F	Fahrenheit
FFU	Fan filter unit
FTU	Fan tower unit
gpm	Gallons per minute
HEPA	High efficiency particulate air
HP	Horsepower
HTO	High temperature oxidation
HVAC	Heating, ventilation, air conditioning
kW	Kilowatt
kWh	Kilowatt-hour
LPCVD	Low pressure chemical vapor deposition
LPM	Liters per minute
MAU	Makeup air units
MCC	Motor control center
MMBtu	Million British thermal units
NTRS	National Technology Roadmap for Semiconductors
PCW	Process cooling water
PE	Plasma etch
psi	Pounds per square inch
PTAB	Project Technical Advisory Board
PVD	Plasma vapor deposition
RA	Arithmetic average

Recirc	Recirculation air units
RTP	Rapid thermal processing
SCADA	System control and data acquisition
scfm	Standard cubic feet per minute
scms	Standard cubic meters per second
ULPA	Ultra low pressure air filter
UPW	Ultrapure water
VAV	Variable air volume
VFD	Variable frequency drive
VLF	Vertical laminar flow
VOC	Volatile organic compound
VSD	Variable speed drive

EXECUTIVE SUMMARY

This report describes a study of energy consumption levels in 14 semiconductor manufacturing facilities (fabs) worldwide, including data from fabs in the United States, Korea, Singapore, Taiwan, France, and the Netherlands. The purpose of this project was to gather baseline data on energy consumed by facilities systems and process tool groups. The report details the survey methodology, including metrics selection, data collection, reporting, and analysis of more than 1,200 records from the participating fabs and presents baseline data on energy consumption levels for fab facility systems, process areas, and process tools.

Most of the data in this report were collected and reported by the participating fabs; however, in a few instances, fabs retained outside contractors to conduct the surveys. The surveys were conducted according to a detailed methodology developed in a previous phase of this study. In the analysis of the data, fab energy use was allocated among eight facilities systems—central plant, makeup air, recirculating air, exhaust, nitrogen, compressed dry air, process cooling water, and ultrapure water (UPW)—and process tools. The use of electrical energy, process cooling water, UPW, and exhaust by process tools was further allocated among six key process areas (patterning, thermal, thin films, dry etch, ion implant, and wafer cleaning).

Comparisons of energy use among diverse fabs were facilitated by using a new metric introduced in this study, kilowatt-hours (kWh) per unit of production, in which "unit of production" is defined as the square inches of wafer processed per year multiplied by the average number of mask layers per wafer processed. This metric provides a new means for quantifying energy efficiency while normalizing for variations in both the production capacity of different fabs and the manufacturing complexity of their products.

The Semiconductor Industry Association's *National Technology Roadmap for Semiconductors* (1998) proposed targets for improving the efficiency of semiconductor manufacturing processes from 9 to 4 kilowatt-hours per square inch ($kWh/inch^2$) (1.4 to 0.6 kWh/cm^2) by 2003. On average, the fabs in this study consumed 7.45 $kWh/inch^2$ (1.15 kWh/cm^2) of wafer processed and 0.393 kWh of electrical energy per unit of production. These figures are consistent with the level of energy efficiency being achieved industry-wide, according to the most recent data available from the U.S. Department of Commerce and Dataquest, which show fab efficiency levels improving from over 20 $kWh/inch^2$ in 1983 to about 9 $kWh/inch^2$ (3.1 kWh/cm^2 to 1.41 kWh/cm^2) by 1995.[1] When compared to each other, the most energy-efficient fabs overall tended to be newer fabs, minienvironment fabs, fabs with extensive monitoring systems, and fabs that had implemented aggressive programs to minimize exfiltration. In addition, fab systems that

[1] 1990–1994 Annual Surveys of Manufacturers, U.S. Department of Commerce, Bureau of Statistics, and Dataquest. These data sources cover fabs in the United States only.

were equipped with high efficiency motors and variable speed drives tended to be among the top performers in each facility system.

The largest category of electrical energy consumption in the fabs studied was process tools, which consumed over 40% of the electrical energy used by the fabs when weighted by fab production levels. The next highest energy-consuming facilities systems were the chillers and recirculating air units, which consumed about 25% and 11% of all the electrical energy used by the fabs, respectively. The analysis of process tool energy used revealed significant electrical energy use in the thin films, dry etch, thermal, and patterning process areas.

This study's findings about average energy consumption levels in fab facilities systems and process areas are generally consistent with previous expectations as well as with the findings of previous studies and adopted industry targets. However, on a case-by-case basis, the data collected for many facilities systems and process areas, particularly those with relatively low average energy consumption, vary widely among the fabs studied. These variations derive from actual differences in the fabs and systems studied (such as fabs in different stages of ramp loading, fabs of different designs, or fabs that produce different products) as well as from possible errors in data measurement, allocation, and reporting (much of the data used in this study were reported by the participating fabs and are unaudited). As a result, sweeping conclusions about baseline energy efficiency levels in the semiconductor industry are not warranted based on this study's findings.

Despite these limitations, the findings can be useful to fab managers, facilities systems engineers, and the semiconductor industry as a whole. Before this study, few wall-to-wall energy surveys had been conducted in fabs, and no uniform methodology for conducting such surveys on a large scale had been published or implemented in the United States, Asia, or Europe. In addition, no standardized metrics for measuring and reporting on fab energy use had been agreed upon. This study represents a first step toward enabling future analyses and comparisons of fab energy efficiency.

1
INTRODUCTION

The international semiconductor industry has worked consistently to reduce

- The amount of energy used by semiconductor manufacturing facilities to minimize pollutants
- The industry's effect on global warming
- Costs

Specific targets adopted within the U.S. semiconductor industry call for reducing energy used in semiconductor manufacturing processes from 9 to 7 kWh/inch^2 (1.4 to 1.1 kWh/cm^2) of wafers processed for existing facilities, and to 4 kWh/inch^2 (0.6 kWh/cm^2) of wafer processed for 300 mm tools by 2003.[2] Those manufacturers who comply with, or work toward, ISO 14000 use industry-wide best practices to continuously improve. In addition, the industry operates under common energy-related constraints including limitation of reliable energy supplies and the threat of business surcharges such as carbon taxes. Although most semiconductor manufacturers have identified and implemented energy efficiency measures in their fabs, the lack of standardized energy consumption data within the semiconductor industry confounds the reliable comparison of energy efficiency among diverse fabs.

To address these issues, International SEMATECH and its member companies sponsored the International Energy Benchmarking Study, a collaborative effort between International SEMATECH member companies and several non-member companies from Korea, Taiwan, Singapore, the Netherlands, and France. In all, 14 fabs from around the world agreed to participate by collecting and sharing data on how much energy was used in fab process areas and facility systems. The shared data would be used to gain a better understanding of overall energy and utility consumption, to identify baseline values of energy consumption, and to share best practices. International SEMATECH encouraged global participation to gain experience in energy conservation worldwide.

International SEMATECH established a Project Technical Advisory Board (PTAB) consisting of representatives of each of the participating companies in addition to representatives of non-participating International SEMATECH member companies, tool manufacturers, and electric utility industry groups. One of the PTAB's first tasks was to identify project objectives and to outline strategies for data collection and analysis. The PTAB identified three main objectives:

- Identify energy and utility consumption levels for overall fab use, facilities systems and subsystems, and process tools for comparison.

[2] Semiconductor Industry Association National Technology Roadmap, 1998, p. 155.

- Identify opportunities for energy reduction in participants' facilities.
- Identify the relationship between design parameters and actual tool energy use in fabs to develop a baseline for comparison with next generation process tools.

This report describes the methodology and findings of a survey implemented as a part of the International Energy Benchmarking Study. To facilitate accurate comparisons of energy use among diverse fabs, International SEMATECH contracted with Planergy, an energy services, engineering, and consulting firm, to develop a methodology for conducting energy surveys of operating fabs, conduct pilot site studies, and to receive, analyze, and report the energy use data collected. The report identifies baseline energy consumption levels within fabs and presents reported energy reduction opportunities and best practices suitable for operating fabs. It is designed to assist facility managers and engineers to better understand energy flows and consumption levels within fabs and ultimately to identify opportunities for energy conservation measures.

2
PROJECT OVERVIEW

Project Strategy

The PTAB defined a strategy to collect, analyze, and produce recommendations from the data. First, detailed wall-to-wall energy surveys and efficiency assessments were performed at two pilot site locations of International SEMATECH members companies. These studies focused on nearly every major facility system, subsystem, and type of manufacturing tool at the pilot sites. In conjunction with the pilot site studies, International SEMATECH and Planergy developed a *Guidance Document* for conducting fab energy surveys. The *Guidance Document* was aimed at helping fabs collect their own energy use data to provide a consistent methodology for data collection among the many participating companies.

The pilot site studies resulted in several significant findings:

- Energy assessments can be conducted in operating fabs without disrupting the operation of the fab. Further, operating process tools can be measured without disrupting the manufacturing operations.
- Approximately 20% of the process tools account for 80% of the tool energy usage.
- Actual electrical energy usage in tools is dramatically less than the manufacturers' design loads.

The PTAB identified the following study design goals, which also affected the project strategy and methodology:

- *Establish baseline values of significant utilities consumption within the fab*. This requirement meant that the survey instrument focused heavily on electricity loads and liquid and gas flows within fabs.
- *Keep survey costs as low as possible and save time*. This requirement drove the PTAB's strategy for allowing participating members to conduct self-assessments, which allowed surveys of multiple fabs to be implemented simultaneously.
- *Limit measurements to those tool types that are among the top 20% of energy consumers*. This goal meant that only the top energy-consuming tools in each process area were selected for surveying.
- *Normalize data to account for variety in production levels at different fabs*. This requirement led the PTAB to the development of "units of production," a measurement that allows for uniform comparability of data among fabs that use different sizes and starts of wafers and different manufacturing processes.

- *Normalize data to account for weather on common metrics*. The consultant evaluated and accounted for the impact of weather in diverse locations.

The PTAB also defined fab process categories, defined metrics for each category, and defined the types of equipment that would be measured in each category. These are summarized in Table 2-1.

Table 2-1
Fab Process Categories

Process/System	Equipment
Patterning	Tracks, coat/dev, stepper
Thermal	Furnaces (horizontal/vertical), rapid thermal processing (RTP), low pressure chemical vapor deposition (LPCVD), including high temperature oxidation (HTO)
Thin-Films	Chemical vapor deposition (CVD) (includes nitride, oxide, metals, silicides), physical vapor deposition (PVD), epitaxy (EPI)
Etch	Plasma, high density plasma etch (PE)
Parts Clean	Equipment parts, quartz (excluding in situ cleans)
Metrology	Microscopes, inspection equipment, scanning electron microscopes
Automated Materials Handling Systems (AMHS)	Wafers, reticles
Chemical Mechanical Polishing (CMP)	CMP, post-CMP clean, backside grinding, slurry treatment
Ion Implant	Implant equipment
Wafer Cleaning/ Wet Benches	All sinks used in wafer cleaning and liquid etching

Project Schedule

The project began in August 1996 when International SEMATECH completed a statement of work for conducting two pilot site energy studies. International SEMATECH selected Planergy as the consultant in October 1996 and convened a PTAB in February 1997. The project then proceeded through three major phases of work:

> Phase 1 (February 1997 to July 1997)—Pilot site energy studies were conducted at two fabs, and the project consultant prepared a *Guidance Document* detailing a consistent methodology for conducting fab energy studies and for measuring data in operating fabs.

Phase 2 (July 1997 to June 1998)—The scope of the data collection effort was expanded to include 14 fabs in the U.S., Asia, and Europe. The participating fabs used the *Guidance Document* to conduct measurements of energy data at their fabs. This phase concluded with the issuance of a first draft report summarizing the data collected.

Phase 3 (June 1998 to February 1999)—The project consultant received and incorporated data revisions and corrections from fabs and identified and conducted detailed follow-up surveys and interviews with top performing fabs. In December 1998, a second draft of the report was issued to the PTAB for review; a final report was submitted to International SEMATECH in February 1999.

The follow-up interviews with top performing fabs served as both a mechanism for gathering more complete information about the design and operation of their systems and a check on the accuracy and validity of the data previously submitted. In a few instances, errors in the data were identified that accounted for some systems' unusually high or low performance. For example, in the categories of chillers, compressed dry air, and UPW water systems, this process of refining data reclassified one of the top performing fabs so that it was no longer be among the top three. These cases are described in the results section.

Project Methodology

Data Collection Methodology

The PTAB determined what type of data to collect, developed a data collection methodology, and worked with the project consultant and teams at participating fabs to effectively collect and report data.

Scope

Data were collected over a 1-year period, although no more than a few months were spent collecting data at any single fab. Many fabs revised their data on multiple occasions because of problems collecting data or appropriately allocating energy consumption to various facilities systems or process areas. The project consultant did not formally audit data submitted by fabs, but did inform them of discrepancies when their data appeared to be outside reasonable bounds and worked with them to identify and correct these discrepancies. Many fabs afterwards remeasured and resubmitted data.

The metrics used in the study are standard units of measurement that are useful for comparisons between and among diverse fabs. For a complete discussion of the metrics used, see the section titled Metrics Used in This Report.

Up to 100 measurements at various points within a fab were collected using a standard data collection survey form. The data were then aggregated to process areas and facilities systems and subsystems. The data collection form is in Appendix A.

The data included information about electricity loads and process cooling water, UPW, and exhaust flow rates for all the major facilities systems and for the manufacturing process tools that use the greatest amount of energy. Data from the two pilot sites were then rolled in with self-reported data from the 12 other fabs and used in the analyses.

Data Collection Methods

The survey broke down energy efficiency and energy consumption data in two ways:

- By facilities systems, including the central chiller plant, makeup air systems, recirculation air systems, exhaust air systems, nitrogen systems, compressed dry air systems, process cooling water systems, UPW systems, and process tools.[3]
- For process tools, electrical energy and process cooling water, UPW, and exhaust flows were further allocated by process areas, including wafer cleaning, dry etch, patterning, thin films, thermal, implant, and chemical mechanical polishing (CMP) and AMHS when appropriate.

Data were collected both on site and from historical reports using a standard survey form to identify the process tool, facilities loads, and efficiency metrics to collect. The survey form, developed using Microsoft Excel, is in Appendix A.

Table 2-2 summarizes information requested in the survey form for each fab. The matrix indicates measurements required of each participant.

[3] The process tools category is not normally considered a facilities system, but in this study it is treated as a system. This allows direct comparison between the energy used by all the process tools in a fab with the energy used by the central plant or recirculating air systems, for example. Not all the fabs studied had every one of the facilities systems listed: for example, some fabs did not have on site nitrogen or compressed dry air plants. These exceptions are mentioned in the detailed descriptions of each system in the Survey Results section.

Table 2-2
Survey Form Summary

Category	Service Area	Flow Air/ Water	Electrical	Natural Gas	Fuel Oil	Temperature Supply	Temperature Return	Temperature Exhaust	Operating Hours	Annual Prediction
Individual Tools								x	x	
Exhaust		x						x	x	
Process Cooling Water		x				x	x		x	
De-Ionized/ Ultra Pure Water		x				x	x		x	
Electrical			x						x	
Overall Tools	x		x						x	x
Overall Facilities	x		x						x	x
Fab Support	x		x						x	x
Recirculating Air-Handling Units	x	x	x			x	x		x	x
Make Up Air-Handling Units		x	x			x			x	x
Exhaust Overall		x	x					x	x	x
General Exhaust		x	x					x	x	x
Solvent Exhaust		x	x					x	x	x
Acid Exhaust		x	x					x	x	x
Ammonia Exhaust		x	x					x	x	x
Process Cooling Water		x	x			x	x		x	x
De-Ionized/ Ultra Pure Water		x	x	x	x	x	x		x	x
Lighting fab	x		x						x	x
Lighting fab Support	x		x						x	x
Compressed Air System		x	x						x	x
Nitrogen Plants		x	x						x	x
Chiller Plant		x	x	x	x	x	x		x	x
Boiler Plant		x	x	x	x	x	x		x	x

For the manufacturing process tools, data on electricity loads and UPW, process cooling water, and exhaust system flow rates were collected while the tools were operating on the fab floor. The survey teams also collected design, or nameplate, parameters from the equipment manufacturer of each tool. These parameters include the manufacturers' stated maximum voltage, current, and loads or flow rates of the tool.[4]

All energy-consuming end uses within the fab were categorized as either facility system loads or tool loads. Facility loads included all equipment used to maintain space conditions or to support the manufacturing process within the fab. Tool loads included the energy consumed directly by the manufacturing process equipment.

Measurement of the data used to establish baseline energy consumption was to include a check and balance method. The check and balance method recommended in the *Guidance Document* applies both "top-down" and "bottom-up" load measurement approaches. A "top-down" load measurement methodology begins at the energy source's point of delivery and allocates consumption to the end-use. In contrast, a "bottom-up" load measurement methodology begins at the end-use and allocates consumption to the source.

Instrumentation

Constant loads were spot-metered, while variable loads were trend-metered. For facility metering, participating fabs used native instrumentation, such as System Control and Data Acquisition (SCADA) systems, or electronic bus metering where available. Because of unbalanced loads and rapid fluctuations, all process tools were to be metered with true kW metering equipment similar to a Dranetz PP1 with a Task 8000 card. Liquid flows were to be measured with native flow meters or ultrasonic non-intrusive meters similar to a Panametrics 686. Air flows were to be measured with standard equipment such as hot-wire anemometers or pitot tubes used by test and balance companies. Airflow meters equivalent to a Shortridge ADM-860 were recommended. Only average hourly loads and the annual hours of load operation were requested from the survey teams.

Types of Data Collected

Table 2-3 shows the categories for which data were collected for facilities systems and subsystems, process areas, and tools and provides a reference to the survey form sheet in Appendix A used to gather information from the project participants. For a more detailed discussion of each of the metrics selected for the study, see Section 3 Survey Results.

[4] In the survey forms developed for this study, survey teams at each fab were asked to provide the designed and average measured electricity loads in kW for each tool studied. Design loads were either taken directly from tool design specifications supplied by the tool manufacturer or derived from nameplate voltage and current ratings, using the formula:

$$\text{Design Load} = \sqrt{3}\, V\, I\, PF$$

in which the square root of three is a constant pertaining to three phased systems, V is the voltage, I is the current, and PF is the power factor. Each fab submitted its facility-wide power factor on the original survey forms, and data collection teams either used the facility-wide power factor, a power factor measured directly at the tool level, or an assumed power factor to derive the designed electricity loads.

Table 2-3
Data Collection by Category

Data Category	Data Collected		Appendix A Sheet #
Facility Information	• General • Cleanroom Class • Support Area	• Sub-Fab • Fab Support	1
Central Plant	• Chillers • Absorption Chillers • Tower Cooling • Chilled Water Auxiliary Systems	• Chiller Plant Building Systems • Thermal Storage Systems • Heating Water Systems • Other Fuel Fired Chillers	2
Makeup Air System	• General Data • Air Handling Unit Data	• Reheat Energy Types	3
Recirculating Air System	• General Data • Air Handling Unit Data		4
Exhaust Air System	• General Exhaust System • Scrubbed Exhaust System • Solvent Exhaust System	• Acid Exhaust System • Ammonia Exhaust System	5
Support Systems	• Nitrogen Plant • Compressed Dry Air Plant • Process Cooling Water • UPW • Hot DI Water System	• Heating Energy Source • Process Vacuum • Fab Support • Lighting	6
Total Tool Load	• Patterning • Thermal • Thin Film • Dry Etch • Metrology	• AMHS • CMP • Ion Implant • Wafer Clean	7
Individual Tool Loads	• Tool Manufacturer/Model • Electricity • Process Cooling Water • UPW	• Exhaust system data, including scrubbed, solvent, acid, and ammonia • Design specifications	8a, 8b

Facility Systems and Subsystems Loads

Data from the two pilot site studies formed the basis for identifying the overall facility loads to be surveyed. The PTAB participants identified a preliminary load list from which key loads were selected for further analysis. The key loads were selected to represent approximately 5% or more of the overall facility load. The PTAB developed the following guidelines to ensure facility load data quality and consistency:

- Weather-dependent loads should be separated from weather-independent loads where reasonable and practical.
- Plant efficiencies should be separated from the plant loads to allow comparisons based upon both usage and generation.
- Loads should be assessed with short-term metering (less than one week metering duration for any load).

Some facility loads, such as lighting, are virtually constant and can be accurately assessed by spot-metering the load and multiplying the load by the annual operating hours, typically 8,760 hours per year in a fab. Other loads, such as cooling loads, may vary on a daily, weekly, or seasonal basis. Loads that did were within the parameters of the project for meter value assessment. Loads that varied over longer than one week, such as seasonal loads, were predicted with short-term metering of critical components and engineering calculation for the annual loads. The team providing the data survey was also responsible for including the load factors in the engineering calculation to predict annual consumption.

Tool Loads

Analysis of the first pilot site study indicated that approximately 80% of the total tool electrical loads in a fab is accounted for by only 20% of the tool loads measured. Each participant in the pilot project provided a list of the top 20% energy-consuming tools in their fab. This was based upon the results of the two pilot studies and is in line with the participants' desire to keep the cost down.

Participants were instructed to provide only the total tool loads by process area if their fab allowed them to measure that data easily; however, most did not. Tool measurement can be very expensive and carries a relatively high degree of risk associated with safety and interruption of tool operation—the PTAB and the project consultant worked to minimize these risks and costs in this project. Targeting the top 20% of the tools made it possible to target future action at the top energy-using tools where presumably the greatest impact can be achieved. The participants chose tools that consumed the highest amount of the following types of energy or flows:

- Electricity—measured in kW of instantaneous demand or kWh of energy
- UPW—measured as a flow (in gallons or liters per minute, for example) through a tool
- Process cooling water (PCW)—also measured as a flow (in gallons or liters per minute, for example) through a tool
- Exhaust—measured as air flow at standard temperature and pressure through a tool

Each participant was asked to collect data from selected tools at their fab. Tool measurement assignments were made in all process areas except CMP, parts clean, metrology, and AMHS, because these are low energy use areas. International SEMATECH staff selected three tools of each type and manufacturer (for a total of 131 tools) to be measured and compared. Three tools of each type were to be measured at different fabs to account for the possible effects of variations in tool usage, wafer recipe, fab operating schedules, and other factors on tool energy use. Consumption data from the tool manufacturers' design specifications were also collected. Tool measurement assignments for each project participant can be found in Appendix B.

Local survey teams chose the data measurement instruments. The type of instrumentation required was identified in the *Guidance Document*, but some flexibility in measurement methods was permitted, based upon requests from a few fabs. Tools were generally measured with true kW meters, which collected multiple samples within each 15-minute recorded data interval. Tool use was metered over a minimum of one complete cycle of the tool, as defined in the *Guidance Document*.

At some fabs, separate feeders served electrical loads for individual tools; other fabs had separate feeders serving groups of tools involved in a single process, such as etch and implant. For fabs where the electrical wiring layout allowed submetering of tools by group without any additional loads, participants provided the submetered values per tool group. Individual tool measurements included electricity, UPW, process cooling water, and exhaust. Compressed dry air, nitrogen, chemicals, and waste flows other than exhaust were not measured.

Assistance in Collecting Data

Participating fabs used the standard survey form to collect data in one of three ways:

- A third-party contractor collected and reported data to International SEMATECH
- A third-party contractor oversaw and assisted internal facility staff who collected the data
- Internal facility staff collected and reported data to International SEMATECH

Figure 2-1 shows the frequency with which each method of data collection was used to implement the survey.

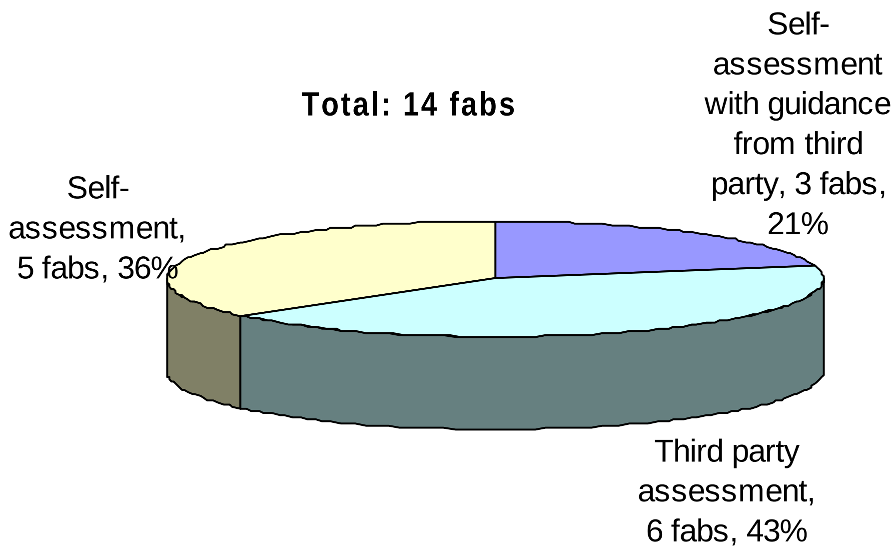

Figure 2-1
Project Participants' Survey Implementation Methods

Potential Sources of Error in Reported Data

In the interpretation of the results and conclusions of this project, several potential sources of error in the data should be noted:

- First, data collection by multiple teams always raises the question of how site-specific conditions affect the prediction or allocation of energy use information. Data collection by independent survey teams, even with aids like the *Guidance Document*, may result in slightly different measurement techniques and calculation methodologies to match the needs of the local teams and facility layout and equipment. This is an accepted limitation of this project to keep the survey cost as low as possible.
- Second, most of the data were unaudited. Error checking procedures that were used were informal and addressed only severely outlying data points.
- Third, the devices used to measure energy, flow rates of liquids and gases, and pressure require precise setup and calibration procedures to yield accurate results. While the *Guidance Document* specified the types of measurement devices that were to be used to gather data, it is not known whether these devices were consistently and appropriately set up and calibrated.
- Fourth, it is possible that simple errors in recording data may have been made, even when measurement devices provided accurate data. However, the iterative process of recording, analyzing, reviewing, and finally remeasuring and resubmitting suspect data points during the second phase of the project likely kept the occurrence and impact of data recording errors to a minimum.

- Finally, errors may have been introduced while translating recorded data to meet the requirements of the data collection form, even when the measuring devices recorded accurate data. These data conversion errors may have resulted, for example, from the need to allocate a single measurement of load or flow to several different systems. In addition, with international participation in this study, some fabs preferred to take measurements in metric units while others preferred English units. To make all the data comparable, some data points needed to be converted to other units by the fabs collecting the data or by the project consultant. While data conversion errors are possible, the occurrence of these errors is believed to be infrequent and the impact on the overall analysis resulting from them is believed to be low.

A more detailed and stringent data collection and reporting methodology would be necessary in future analyses of energy consumption to overcome these potential sources of error.

Data Analysis Methodology

Scope

Data from the two pilot site studies was combined with the elf-reported data from the 12 other fabs. The resulting database, consisting of more than 1,200 records, was used to determine facility, process area and tool efficiencies and to normalize these values for comparison among fabs. To effectively determine efficiency levels while considering variability in other factors, the data analysis included the development of methods to normalize the data. Output reports were based on requirements from the PTAB.

Normalization of Data

The submitted data was normalized to compensate for the variation in facility production levels, utility costs, and weather.

Facility Production Level

The surveyed fabs varied in size, cleanroom class, and complexity of their products. The PTAB determined that normalization of the facilities for factors other than weather could be accomplished using a production index for the study. The production index simply normalizes the energy use of tools, facilities systems, or process areas by units of production. The elements of units of production are as follows:

- Number of wafers started per year—a common measure of production volume
- Area of the wafers produced—either 150-mm (6-in.) or 200-mm (8-in.) wafers were used
- Average number of mask layers per wafer—an indicator of the complexity of the manufacturing process

The product of these values, as shown in the following formula, is the unit of production used to normalize the data for differences among facility operation, size, and type:

Units of Production = Wafer Starts/Year * Wafer Area (in^2) (mm^2) * Mask Layers

This method of normalization is newer and more complex than preceding methods.[5]

Energy Cost

Energy cost for electricity and fuel (natural gas, diesel, etc.) varied significantly from fab to fab. Most of the fabs' electrical energy costs were between U.S.$0.04/kWh and U.S.$0.06, although one fab's electrical energy cost was slightly lower than the rest at U.S.$0.037, and one fab's cost was significantly higher than all others at U.S.$0.160. This issue was addressed in the two pilot site studies. The simplest method of normalizing cost data from fab to fab was to use an average energy cost of U.S.$0.05/kWh for electricity and U.S.$3/MMBtu for fuel.[6] This method of normalization was used only for the economic evaluation of self-reported energy savings by fabs.

Weather

During development of the survey form, the impact of weather was minimized by reviewing the loads and anticipating weather dependence. The survey form was designed to isolate weather-dependent loads from weather-independent loads. Data collection was based upon isolating the loads by temperature dependence and then adjusting the individual loads as required. It was determined that a threshold minimum value of 10% variation in loads attributable to variation in climate was necessary before a load would be considered for weather normalization.

Initial modeling and field data indicated that some loads typically considered weather-dependent were relatively stable in a fab environment. For example, the vertical laminar flow (VLF) cooling load data shown in Figure 2-2 (also called the recirculating fan cooling load) obtained from one of the participating fabs showed a sensitivity of only 2% per degree F (C) of outside air temperature. This low sensitivity is consistent with the computer modeling of the recirculation load and probably results from the standard isolation of fab loads from outdoor air loads. A 10% variation in recirculating system loads, isolated from outdoor air loads, would require a 55°F (13°C) differential in average annual temperature among the fabs surveyed. The highest average annual temperature was 81°F (27°C) and the lowest was 45°F (7°C), resulting in a maximum temperature differential among the fabs of just 36°F (2°C)—far less than 55°F (13°C) and well below the 10% threshold.

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[5] Other normalization procedures commonly used in the industry include normalizing fab energy use by wafer starts per month (or year) or by the area of wafer processed in a month (or year). These methods account for variation in production but not for variation in the manufacturing complexity of the product. The PTAB members agreed that multiplying by the average number of mask layers would be a simple method for taking the manufacturing complexity of a chip into account. Process geometry, essentially the control tolerance in the manufacture of semiconductors, was also discussed by the PTAB as a potential variant. Unlike mask layers, wafer area, and wafer starts, geometry does not appear to have a threshold level which can be used for comparison, and at least part, if not all, of the impact of process geometry may be accounted for by the number of mask layers.

[6] Source: Bureau of Labor Statistics, Annual Survey of Manufacturers, 1989-1996.

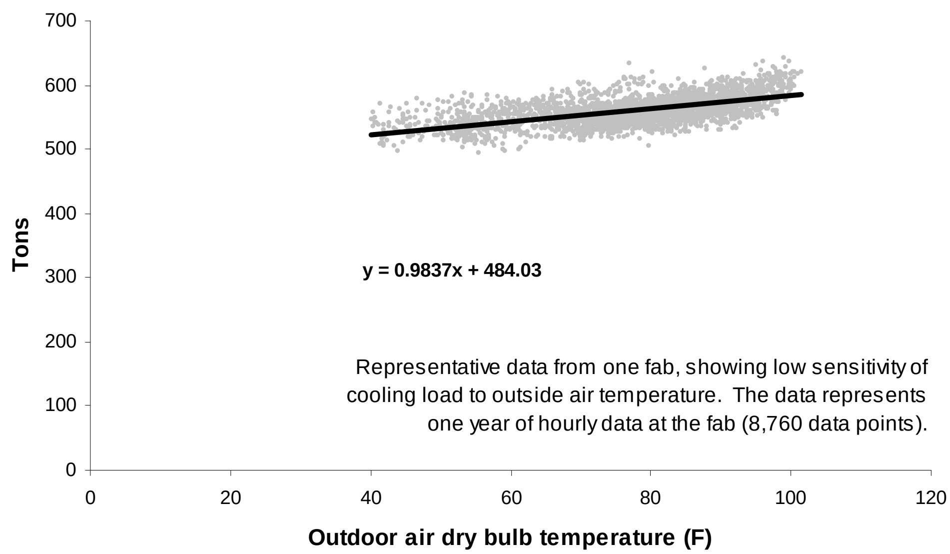


Figure 2-2
Sensitivity of Vertical Laminar Flow Sensible Cooling Load to Outdoor Air Temperature at One Fab

As a result, fab recirculating fan cooling loads are considered weather-independent. The outdoor makeup air loads, however, are weather-dependent. Figure 2-3 shows the relationship between outdoor air cooling loads and average annual temperature for a range of typical fab locations. The analysis is based upon 1000 cubic feet per minute (cfm) (1,698 cubic meters per hour [cmh]), of makeup air and a 41°F (5°C) supply air temperature. The cooling load includes both the sensible and latent coil loads. Heating load is not included in the analysis.

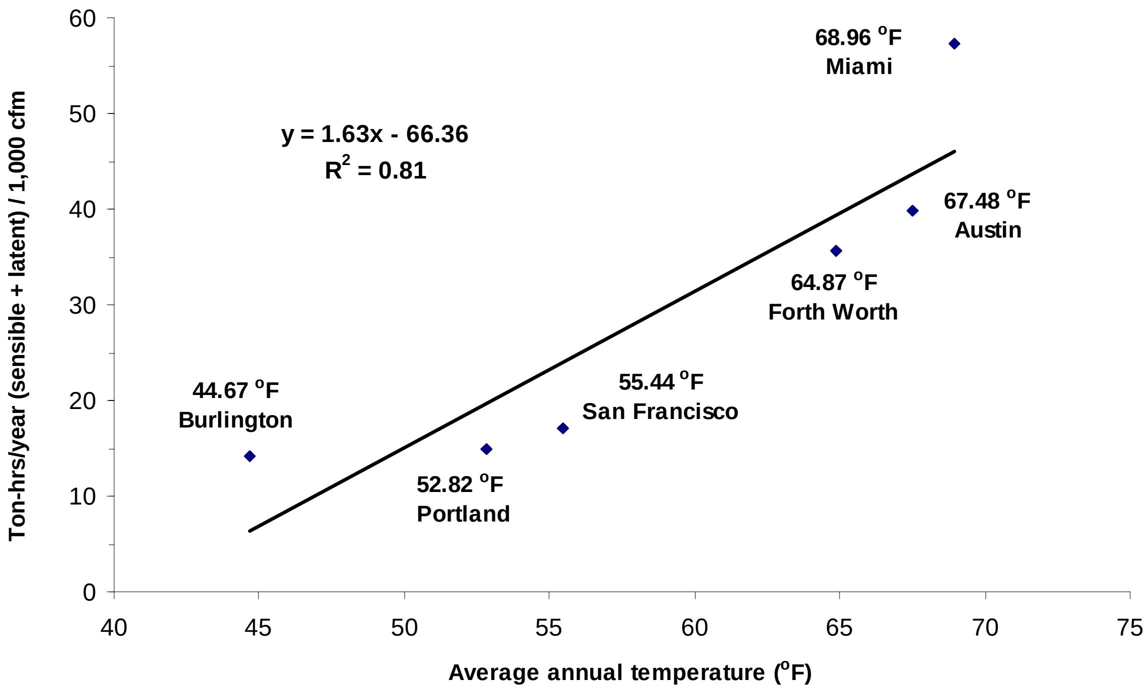


Figure 2-3
Required Outdoor Air Cooling Load at Seven U.S. Fabs

Each participating fab submitted data on the total cooling load of the central plant and separate data on the amount of cooling received by the makeup air system, recirculating air system, process cooling water system, and other facility systems. This double reporting process was used to verify the accuracy of the cooling load data. If data were accurately measured and reported by all fabs, the allocated cooling loads would be expected to be 100% of the reported central plant cooling load. However, the sum of the cooling loads reported by most of the fabs did not equal the cooling output from the central plant. Individual cooling loads accounted for only a median value of 62% of the total central plant output.

The disaggregation of the cooling load by metering can be a difficult process. If the fab does not have expensive native metering capability installed—and few fabs in this study do—then conducting such measurements and performing the disaggregation accurately and consistently can be extremely difficult. From the data collected in this survey, it appears that this task was too difficult to perform accurately and consistently given the design parameters of this study, which relied extensively on self-measurement and self-reporting. This suggests some serious inconsistencies in the underlying data on cooling system loads, and prevents weather normalization from being implemented as originally expected.[7]

[7] Normalizing for weather is possible in this situation, but given the inconsistencies in the underlying data the results would be unreliable.

Types of Analysis Performed

The following analysis tasks were performed:

- Energy usage averages were identified for facilities systems and process tools.
- Potentially achievable energy efficiency values were identified for facilities systems and process tools. These values were defined as the midpoint between the minimum and average values of kWh per unit of production calculated for each of the 14 participating fabs.

Limitations of Data Analysis

From the perspective of statistical analysis of the data, the design of this study has three main weaknesses:

- Small sample size. The 14 participating fabs represent less than 1% of all fabs worldwide. This small number makes observed relationships between variables—e.g., between the cost of energy and total fab energy efficiency—difficult to corroborate from a robust statistical perspective. That is, the relationships between pairs of variables are not statistically significant at levels of confidence (80, 95, or 99%) that would normally be required to support generally applicable conclusions about fab energy efficiency.
- Non-random sampling. All participating companies are International SEMATECH members that agreed to conduct energy audits, and the fabs selected for inclusion in this study are not necessarily representative of the fabs operated by the participating company or of the worldwide base of operating fabs. A more robust study design would use random sampling methods to select the fabs to be studied.
- Inability to independently isolate subsystems to discern their impact on the system as a whole. If the goal is to examine the energy efficiency of individual systems within a fab, an underlying assumption in statistical analysis of energy efficiency data is that separate systems are not dependent upon one another. Although the methodology used in this study for separating facility loads attempts to handle this concern, it does not, and in fact cannot, do so completely. For example, the process cooling water system typically depends upon the chiller system to provide cooling to water. The data measurement methodology used in this study attempts to separate these systems by accounting for the cooling energy in the measurements of the chiller system and accounting for energy used to pump water through the process cooling water loops in the measurement of the process cooling water system. But even with this division in place, there are still dependencies between the systems. If the chiller system provides less cooling to the process cooling water system, the process cooling water system may still need to use more energy in pumping water more quickly through its loops.
- These limitations are by no means fatal flaws in the validity of this study. But they limit the analytical scope of the project to the non-statistical realm. This study succeeds in describing and comparing the energy efficiency of the facilities systems and process tools surveyed while conceding that the results cannot be generalized with confidence to a wider population of fabs.

Data Reporting Methodology

Metrics Used in This Report

One of the goals of this project was to estimate baseline values of energy consumption that could facilitate comparison of energy consumption data at diverse fabs. The survey instrument was designed to help participating fabs measure and record certain tool and facility loads. The load data was used to calculate output metrics that would be useful for comparisons of energy use among systems or fabs. Metrics are defined as calculated values that describe the energy use of a system in terms of output. Two types of metrics were calculated: efficiency metrics and normalized metrics.

Efficiency metrics describe the operating efficiency of a system in terms of a ratio of units of input to units of output. The precise units of an efficiency metric may vary depending on the type of system being analyzed. For example, the efficiency metric for makeup air systems is presented in terms of cubic feet per minute of air flow per kilowatt of energy demand by the makeup air fans. In contrast, the efficiency metric for UPW systems is presented in terms of kilowatt-hours of electricity used by the pumps per gallon of UPW pumped through the system. The units used in the efficiency metrics are standard efficiency measures commonly used among facilities professionals. Efficiency metrics are analogous to the gas mileage ratings applied to automobiles—they allow for comparison among models while realizing that actual performance will vary depending on operating characteristics and environmental conditions. Efficiency metrics are therefore useful for comparing the operating efficiency of a system or subsystem to manufacturers' claims or to similar systems in use in other types of facilities.

Normalized metrics present efficiency measures for all systems using the same units. For this study, Planergy and the PTAB agreed on a normalized metric that would be useful to the semiconductor manufacturing industry. Normalized metrics are consistently presented in this report in terms of kilowatt-hours of electricity used by the system per unit of production. The numerator of these metrics, kilowatt-hours of electricity used by the system, is not always immediately available for all fab systems. The denominator of these metrics, units of production, reflects the throughput of a fab. Normalized metrics are therefore useful for understanding to what extent the energy used by system or subsystem contributes to overall fab productivity.

In calculating the two metrics, the study team created graphs showing how fabs performed on many other metrics, some that were particular to individual systems in the fab, others that evaluated performance of the total fab. Many of these graphs are shown in Appendix G, Additional Graphs and Scatter Plots.

Types of Reports Generated

The reports were designed to enable participating companies to define the average energy consumption for facilities and process areas, and, using site-specific facility information, to then identify opportunities to reduce energy consumption.

Data Area	Type of Report Created
Facilities Systems and Process Tools	• System efficiency (efficiency by type of energy used) • Normalized energy usage by "units of production"
Process Tools	• Energy use allocation to process areas • Designed and measured energy consumption by tool

Note on Masking of Data Within This Report

Every effort to include as much of the data collected while still preserving the confidentiality of fab operating data. As a convention in this report, randomly assigned numbers between one and 14 identify data from individual fabs. This convention allows readers to track an individual fab's performance without identifying the fab by name.

3
SURVEY RESULTS

This section reviews survey results for facilities systems and subsystems and process areas. The facilities results section describes general findings, defines the facilities systems and subsystems, and presents results. The process area section describes general findings and presents significant data for key process areas in the context of the type of energy consumed.

General Findings

General Descriptions of the Fabs Studied

This section presents summary data on each of the 14 fabs that participated in this study.

Fab 1 is located in a temperate climate in Europe with an average annual temperature of 53°F (12°C). The 5-year old fab uses 200 mm wafers in its production process. The cleanroom contains 55,952 square feet (5,198 square meters) of production area, is of a ballroom design, and is rated at class 0.1–100 with a minimum geometry of 0.25 µm. Throughput averages 276,000 wafer starts per year, producing end products with an average of 22 mask layers. The fab's peak electrical load is 14,000 kW; average load is 10,850 kW. Design cooling load is 0.0603 tons per square foot (0.65 tons per square meter). Average raw water use at the fab totals approximately 20 million gallons (75 million liters) per month.

Fab 2 is located in a hot, humid climate in Asia with an average annual temperature of 72°F (22°C). The 3-year old fab uses 200 mm wafers in its production process. The cleanroom contains 174,785 square feet (16,238 square meters) of production area, is of a ballroom design but with minienvironments, and is rated at class 100–1,000 with a minimum geometry of 0.20 µm. Throughput averages 775,824 wafer starts per year, producing end products with an average of 19.5 mask layers. The fab's peak electrical load is 27,264 kW; average load is 24,857 kW. The design cooling load is 0.0066 tons per square foot (0.07 tons per square meter). Average raw water use at the fab totals approximately 48 million gallons (180 million liters) per month.

Fab 3 is located in a hot, humid climate in Asia with an average annual temperature of 72°F (22°C). The 4-year old fab uses 150 mm wafers in its production process. The cleanroom contains 51,594 square feet (4,793 square meters) of production area, is of a ballroom and bay and chase design, and is rated at class 1, 10, and 1,000 with a minimum geometry of 0.3 µm. Throughput averages 378,000 wafer starts per year, producing end products with an average of 25 mask layers. The fab's peak electrical load is 14,086 kW; average load is 12,487 kW. The design cooling load is 0.0154 tons per square foot (0.17 tons per square meter). Average raw water use at the fab totals approximately 17 million gallons (66 million liters) per month.

Fab 4 is located in a hot, humid climate in Asia with an average annual temperature of 72°F (22°C). The 3-year old fab uses 200 mm wafers in its production process. The cleanroom contains 36,261 square feet (3,369 square meters) of production area, is of a ballroom design, and is rated at class 0.1 with a minimum geometry of 0.25 µm. Throughput averages 259,980 wafer starts per year, producing end products with an average of 20 mask layers. The fab's peak electrical load is 13,997 kW; average load is 9,140 kW. The design cooling load is 0.0221 tons per square foot (0.24 tons per square meter). Average raw water use at the fab was not reported.

Fab 5 is located in a temperate climate in Asia with an average annual temperature of 53°F (12°C). The 3-year old fab uses 200 mm wafers in its production process. The cleanroom contains 66,804 square feet (6,206 square meters) of production area, is of a ballroom and bay and chase design, and is rated at class 1, 10, and 1,000 (minimum geometry was not reported). Throughput averages 360,000 wafer starts per year, producing end products with an average of 26.0 mask layers. The fab's peak electrical load is 20,900 kW; average load is 18,800 kW. The design cooling load was not reported. Average raw water use at the fab totals approximately 17 million gallons (63 million liters) per month.

Fab 6 is located in a hot, humid climate in the United States with an average annual temperature of 65°F (18°C). The 13-year old fab uses 150 mm wafers in its production process. The cleanroom is a ballroom design. Production area, minimum geometry, the fab's class rating, wafer starts per year, and average mask layers were not reported. The fab's peak electrical load is 14,600 kW; average load is 13,700 kW. The design cooling load is 0.037 tons per square foot (0.40 tons per square meter). Average raw water use at the fab totals approximately 6 million gallons (23 million liters) per month.

Fab 7 is located in a hot, humid climate in Asia with an average annual temperature of 81°F (27°C). The 7-year old fab uses 200 mm wafers in its production process. The cleanroom contains 41,318 square feet (3,838 square meters) of production area, is of a ballroom design, and is rated at class 1 with a minimum geometry of 0.32 µm. Throughput averages 144,000 wafer starts per year, producing end products with an average of 26 mask layers. The fab's peak electrical load is 8,383 kW; average load is 6,478 kW. The design cooling load is 0.0049 tons per square foot (0.05 tons per square meter). Average raw water use at the fab totals approximately 27 million gallons (103 million liters) per month.

Fab 8 is located in a hot, humid climate in Asia with an average annual temperature of 81°F (27°C). The 3-year old fab uses 200 mm wafers in its production process. The cleanroom contains 75,320 square feet (6,997 square meters) of production area, is of a ballroom design with incorporated minienvironments, and is rated at class 100 with a minimum geometry of 0.35 µm. Throughput averages 360,000 wafer starts per year, producing end products with an average of 15 mask layers. The fab's peak electrical load is 28,000 kW; average load is 14,000 kW. The design cooling load is 0.0125 tons per square foot (0.13 tons per square meter). Average raw water use at the fab totals approximately 30 million gallons (114 million liters) per month.

Fab 9 is located in a hot, humid climate in the United States with an average annual temperature of 65°F (18°C). The 14-year old fab uses 150 mm wafers in its production process. The cleanroom contains 59,100 square feet (5,490 square meters) of production area, is of a ballroom and bay and chase design, and is rated at class 1–10 with a minimum geometry of 0.65 µm. Throughput averages 564,000 wafer starts per year, producing end products with an average of 15 mask layers. The fab's peak electrical load is 11,200 kW; average load is 9,765 kW. The design cooling load was not reported. Average raw water use at the fab totals approximately 25 million gallons (95 million liters) per month.

Fab 10 is located in a hot, humid climate in the United States with an average annual temperature of 68°F (20°C). The 3-year old fab uses 200 mm wafers in its production process. The cleanroom contains 43,360 square feet (4,028 square meters) of production area, is of a ballroom design, and is rated at class 0.1 with a minimum geometry of 0.25 µm. Throughput averages 240,000 wafer starts per year, producing end products with an average of 20.5 mask layers. The fab's peak electrical load is 18,000 kW; average load is 13,216 kW. The design cooling load is 0.0366 tons per square foot (0.39 tons per square meter). Average raw water use at the fab totals approximately 105 million gallons (397 million liters) per month.

Fab 11 is located in a temperate climate in the United States with an average annual temperature of 61°F (16°C). The 11- year old fab uses 200 mm wafers in its production process. The cleanroom contains 50,000 square feet (4,645 square meters) of production area, and is rated at class 10–1,000 with a minimum geometry of 0.25 micron (fab design was unreported). Throughput averages 267,840 wafer starts per year, producing end products with an average of 14 mask layers. The fab's peak electrical load is 14,400 kW; average load is 13,700 kW. The design cooling load is 0.065 tons per square foot (0.7 tons per square meter). Average raw water use at the fab totals approximately 41 million gallons (155 million liters) per month.

Fab 12 is located in a cold, humid climate in the United States with an average annual temperature of 45°F (7°C). The 15-year old fab uses 200 mm wafers in its production process. The cleanroom contains 178,000 square feet (16,536 square meters) of production area, is of a ballroom and bay and chase design, and is rated at class 10–1,000 (minimum geometry was not reported). The fab did not release information on wafer starts or number of mask layers. The fab's peak electrical load is 19,035 kW; average load is 15,345 kW. The design cooling load is 0.0204 tons per square foot (0.22 tons per square meter). Average raw water use at the fab totals approximately 56 million gallons (212 million liters) per month.

Fab 13 is located in a cold, humid climate in Europe with an average annual temperature of 51°F (11°C). The 11-year old fab uses 150 mm wafers in its production process. The cleanroom contains 42,653 square feet (3,962 square meters) of production area, is of a bay and chase design, and is rated at class 10–100 with a minimum geometry of 0.60 µm. Throughput averages 238,000 wafer starts per year, producing end products with an average of 14.1 mask layers. The fab's peak electrical load is 5,300 kW; average load is 4,836 kW. The design cooling load is 0.0256 tons per square foot (0.28 tons per square meter). Average raw water use at the fab totals approximately 6 million gallons (22 million liters) per month.

Fab 14 is located in a temperate, humid climate in the United States with an average annual temperature of 53°F (12°C). The 7-year old fab uses 200 mm wafers in its production process.

The cleanroom contains 68,500 square feet (6,364 square meters) of production area, is of a ballroom design, and is rated at class 1 with a minimum geometry of 0.35 µm. Throughput averages 280,800 wafer starts per year, producing end products with an average of 21 mask layers. The fab's peak electrical load is 12,816 kW; average load is 10,180 kW. The design cooling load is 0.0336 tons per square foot (0.36 tons per square meter). Average raw water use at the fab totals approximately 15 million gallons (57 million liters) per month.

The average age of the facilities was 7.2 years; this average includes several facilities that were not originally fabs. The average age drops to 5 years when only the time since the last major wafer retrofit is considered. Interestingly, the distribution of the age of participating fabs is skewed toward extremes. Seven of the 14 fabs are 5 years old or younger, two are between 6 and 10 years old, and five are 11 years old or older. At least one of the older fabs actually comprises several separate fabs, the oldest of which is reported as the fab's age.

Manufacturing diversity included 150 mm and 200 mm wafers. Cleanroom classification ranged from 0.1 to 1000; all the fabs were sub-micron geometry. Fab types included ballroom, bay and chase, and minienvironments. Fab processing areas varied from 36,000–180,000 ft^2 (3,400 to 16,500 m^2) with an average area of 72,600 ft^2 (6,750 m^2). A summary of general fab parameters is shown in Table 3-1. The wafer diameter, wafer starts per year, average number of mask layers, and units of production are shown for each fab in the table. Data on wafer starts per year and mask layers for two fabs were not reported, but the units of production for those fabs is shown. As shown in the table, four of the fabs surveyed use 150 mm wafers while ten use 200 mm wafers.

Cleanroom type is defined as either ballroom, bay and chase, minienvironment, or a combination of these types. Six of the fabs are strictly ballroom type facilities. Of these, five use 200 mm wafers while one uses 150 mm wafers. Three of the six ballroom facilities are older than five years old. Four fabs have ballroom combined with bay and chase designs; two are ballroom with minienvironments. The cleanroom type at one fab was unspecified. Six fabs are in the United States, six are in Asia, and two are in Europe.

Table 3-1
General Facility Data

Fab Number	Wafer Diameter		Wafer Starts per Year	Average Mask Layers	Annual Units of Production	Age of Fab	Production Area		Location[1]	Average Annual Temp.		Climate[2]	Cleanroom		Minimum geometry	Electric load		Design cooling load	
	in.	mm			million	years	ft^2	m^2		F	C		Type[3]	Class	micron	Peak kW	Average kW	tons/ft^2	tons/m^2
1	8	200	276,000	22.0	305	5	55,952	5,198	E	53	12	T	B	0.1-100	0.25	14,000	10,850	0.0603	0.65
2	8	200	775,824	19.5	760	3	174,785	16,238	A	72	22	H,Hu	B, ME	100-1000	0.20	27,264	24,857	0.0066	0.07
3	6	150	378,204	25.0	267	4	51,594	4,793	A	72	22	H,Hu	B, BC	1, 10, 1000	0.30	14,086	12,487	0.0154	0.17
4	8	200	259,980	20.0	261	3	36,261	3,369	A	72	22	H,Hu	B	0.1	0.25	13,997	9,140	0.0221	0.24
5	8	200	360,000	26.0	470	3	66,804	6,206	A	53	12	T	B, BC	1,10,1000		20,900	18,800		
6	6	150			244	13			US	65	18	H,Hu	B			14,600	13,700	0.0370	0.40
7	8	200	144,000	26.0	188	7	41,318	3,838	A	81	27	H,Hu	B	1	0.32	8,383	6,478	0.0049	0.05
8	8	200	360,000	15.0	271	3	75,320	6,997	A	81	27	H,Hu	B, ME	100	0.35	28,000	14,000	0.0125	0.13
9	6	150	564,000	15.0	239	14	59,100	5,490	US	65	18	H,Hu	B, BC	1 - 10	0.65	11,200	9,765		
10	8	200	240,000	20.5	247	3	43,360	4,028	US	68	20	H,Hu	B	0.1	0.25	18,000	13,216	0.0366	0.39
11	8	200	267,840	14.0	188	11	50,000	4,645	US	61	16	T		10-1000	0.25	14,400	13,700	0.0650	0.70
12	8	200			351	15	178,000	16,536	US	45	7	C,Hu	B, BC	10, 1000		19,035	15,345	0.0204	0.22
13	6	150	238,800	14.1	95	11	42,653	3,962	E	51	11	C,Hu	BC	10-100	0.60	5,300	4,836	0.0256	0.28
14	8	200	280,800	21.0	296	7	68,500	6,364	US	53	12	T,Hu	B	1	0.35	12, 816	10,180	0.0336	0.36

[1]A=Asia, E=Europe, US=United States

[2]C=Cold, H=Hot, T=Temperate, Hu=Humid

[3]B=Ballroom, BC=Bay & chase, ME=minienvironment

Note: Data on wafer starts, mask layers, production area, and minimum geometry were not reported by fab 6. Data on wafer starts and mask layers were not reported by fab 12.
Blank cells and zeros indicate data not submitted. Data appears as reported by respondent.

Overall Electric Energy Allocation in Fabs

Figure 3-1 displays the allocation of electrical energy consumption among eight facilities systems and process tools, weighted by the units of production of each fab.

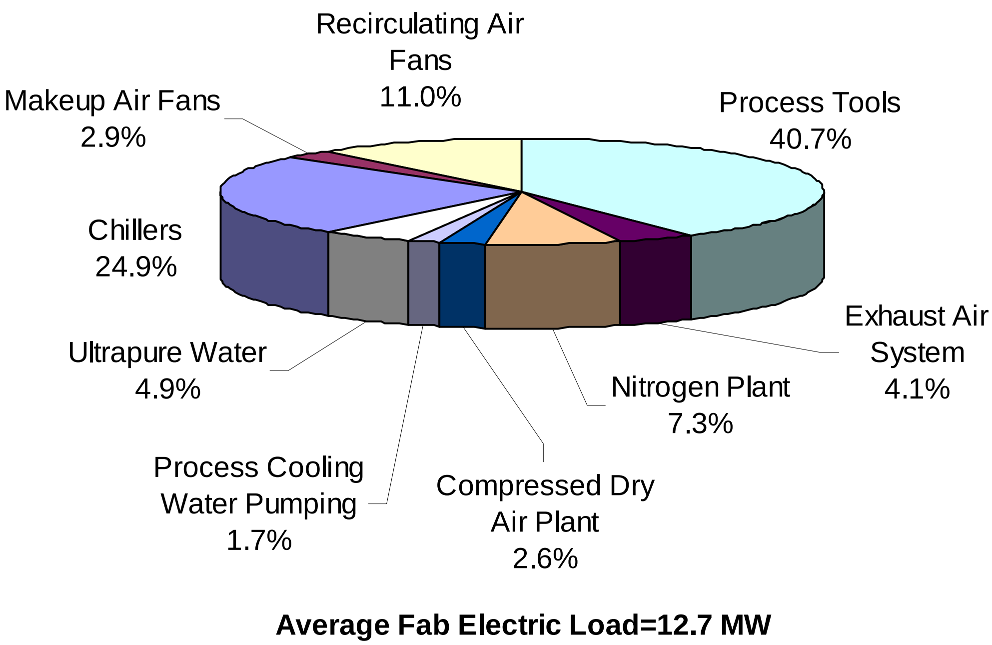


Figure 3-1
Weighted Average Electrical Consumption by Facilities Systems

The measured components of each of these systems is described below:

1. Chillers and Auxiliary Systems—average energy used by the chillers, pumps, cooling towers, and the facility housing these systems
2. Makeup Air Fans—fan electrical energy only
3. Recirculating Air Fans—fan electrical energy only
4. Nitrogen Plant—total electrical energy used by the nitrogen plant
5. Compressed Dry Air Plant—average energy used by compressed dry air plant
6. Process Cooling Water Pumping—average energy used by the pumps supplying process cooling water (chiller energy is included in the chilled water plant data)
7. Exhaust Air System—energy used by the exhaust fan motors and scrubbers
8. UPW—all energy required to create distribute and reclaim DI/UPW water
9. Process Tools—all electrical energy directly used by the process tools

The pie chart reveals important findings about energy use in semiconductor manufacturing facilities. Specifically, the chart shows that process tools consume 40.7% of the energy, making them the single largest category of energy consumers. The second highest level of consumption was for chillers systems, which consumed approximately 24.9% of the energy. Recirculating air fans were the third highest consumers at 11.0%; makeup air fans consumed another 2.9%. The chillers, recirculating air, and makeup air systems work together to maintain consistent operating conditions throughout fab facilities. Together, they comprise 38.8% of the energy consumed in the fabs studied. These findings demonstrate that nearly 80% of the energy consumed in operating fabs is directly related to the process tools and the chillers, recirculating air, and makeup air systems.

The methodology used in creating Figure 3-1 is as follows. Data were collected from the 14 fabs (n=14). From this, ten relevant data points used in the calculation of fab energy allocations (see Figure 3-1) were calculated:

A.) The fab's annual units of production (UOP, derived from reported wafer starts per year * average number of mask layers * square inches (square millimeters) of wafer) and

B. – J.) The fab's annual energy usage (in kWh) by process tools and by each of the eight facility areas (chillers/central plant, recirculating air, makeup air, UPW, process cooling water, exhaust air, nitrogen, and compressed dry air)

These data points can be represented in a matrix, as shown below:

	Fab Number		
	1	**…**	**14**
A. Annual fab units of production (UOP)	A_1	…	A_{14}
Annual energy use by:			
B. Process tools (kWh)	B_1	…	B_{14}
C. Chillers/central plant (kWh)	C_1	…	C_{14}
D. Recirculating air systems (kWh)	D_1	…	D_{14}
E. Makeup air systems (kWh)	E_1	…	E_{14}
F. Ultrapure water (kWh)	F_1	…	F_{14}
G. Process cooling water (kWh)	G_1	…	G_{14}
H. Exhaust air (kWh)	H_1	…	H_{14}
I. Nitrogen system (kWh)	I_1	…	I_{14}
J. Compressed dry air system (kWh)	J_1	…	J_{14}
Total kWh (sum of B through J)	T_1	…	T_{14}

Next, the annual energy use in each fab (B–J) was allocated among the different facilities systems in the fab, expressing the allocation as a portion of the total energy used in each fab. The entries in each column sum to 1.0 (for the remainder of this discussion, an abbreviated version of the matrix is used as an example of the calculations performed on all lines):

	Fab Number		
	1	**…**	**14**
A. Annual fab units of production (UOP)	A_1	…	A_{14}
Annual energy use by:			
B. Process tools (kWh)	B_1/T_1	…	B_{14}/T_{14}
…	…	…	…
J. Compressed dry air system (kWh)	J_1/T_1	…	J_{14}/T_{14}
Total kWh (sum of B through J)	1.0	1.0	1.0

Finally, to weight the allocations by the production of each fab, the value in each cell is multiplied by the units of production for the fab (row A), and the rows are summed to the right.

	Fab Number			
	1	**…**	**14**	***Total***
A. Annual fab units of production (UOP)	A_1	…	A_{14}	
Annual energy use by:				
B. Process tools (kWh)	$A_1(B_1/T_1)$	…	$A_{14}(B_{14}/T_{14})$	Σ_B
…	…	…	…	…
J. Compressed dry air system (kWh)	$A_1(J_1/T_1)$	…	$A_{14}(J_{14}/T_{14})$	Σ_J
Total kWh (sum of B through J)				

The summed values Σ_B through Σ_J are then expressed in the pie chart shown in Figure 3-1. This method ensures that the energy allocation of fabs with higher production levels (as expressed in units of production) is weighted more heavily in the final analysis than the energy consumption of fabs with smaller production levels.

General Indices of Fab Performance

Production Index

The total annual units of production for each of the 14 fabs are shown in Figure 3-2, below. This value is defined as the production index. Including wafer starts, mask layers, and the area of the wafer in the production index allows the index to be sensitive to the energy intensity of the production process from fab to fab.

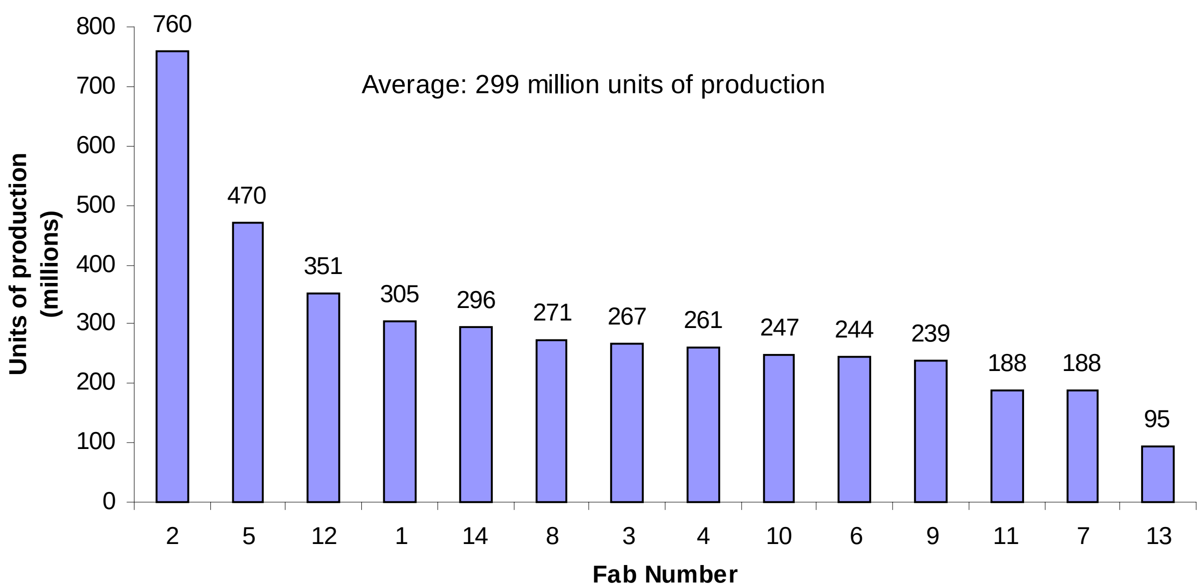


Figure 3-2
Production Index

Among the top three fabs in terms of the production index (fabs 2, 5, and 12), two are located in Asia and one in the United States. All three use 200 mm wafers in their production process. Two of the fabs are just 3 years old; the other, fab 12, reported its age as 15 years. Fab 2 reported 775,824 wafer starts per year (the highest reported) with an average of 19.5 mask layers; fab 5 reported 360,000 wafer starts per year with an average of 26 mask layers (together with fab 7, the highest number of mask layers reported); fab 12 did not report wafer starts per year or mask layers, but did report aggregate units of production.

Space Utilization Index

The space utilization index is another indicator of the productivity of the facility. The index is defined as the units of production divided by the total floor area used for production in the fab. It is a measure of the production density within the production area and of throughput of the fab. Space utilization directly affects the sizing of the recirculation air handling and makeup air handling systems along with the central plant supporting these systems. Values of the space utilization index are shown in Figure 3-3.

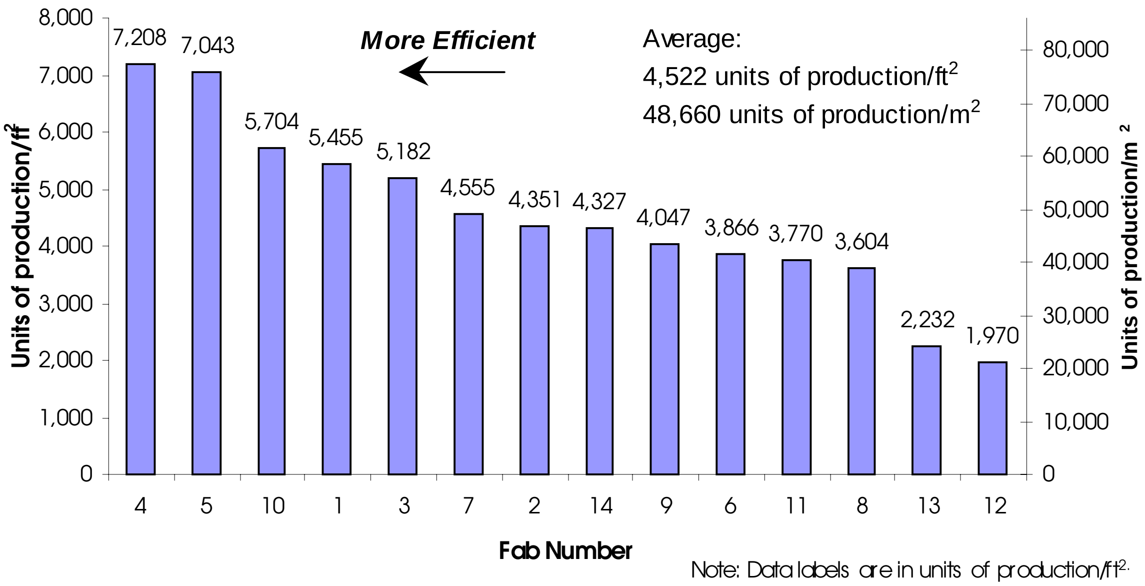


Figure 3-3
Space Utilization Index

Space utilization index values averaged 4,522 units of production/ft^2 (48,660 units of production/m^2), and ranged from a high of 7208 units of production/ft^2 to a low of 1970 units of production/ft^2.

The top three fabs in terms of the space utilization index were fabs 4, 5, and 10. Fabs 4 and 5 are located in Asia; fab 10 is located in the United States. All of these fabs were 3 years old and used 200 mm wafers in their production process. Fab 4 reported the smallest production area (36,261 ft^2, 3,369 m^2) of any fab in the study; fab 10's reported production area (43,360 ft^2, 4,028 m^2) was the fourth smallest. Fab 5's reported annual units of production (470 million) were the second largest reported by any fab.

Electrical Utilization Index

The electrical utilization index is defined as a fab's total annual energy consumption divided by its units of production. Electricity usage per unit of production shows how efficiently a facility is using its energy resources toward production. Figure 3-4 presents data on the electrical utilization index of each fab in the study.

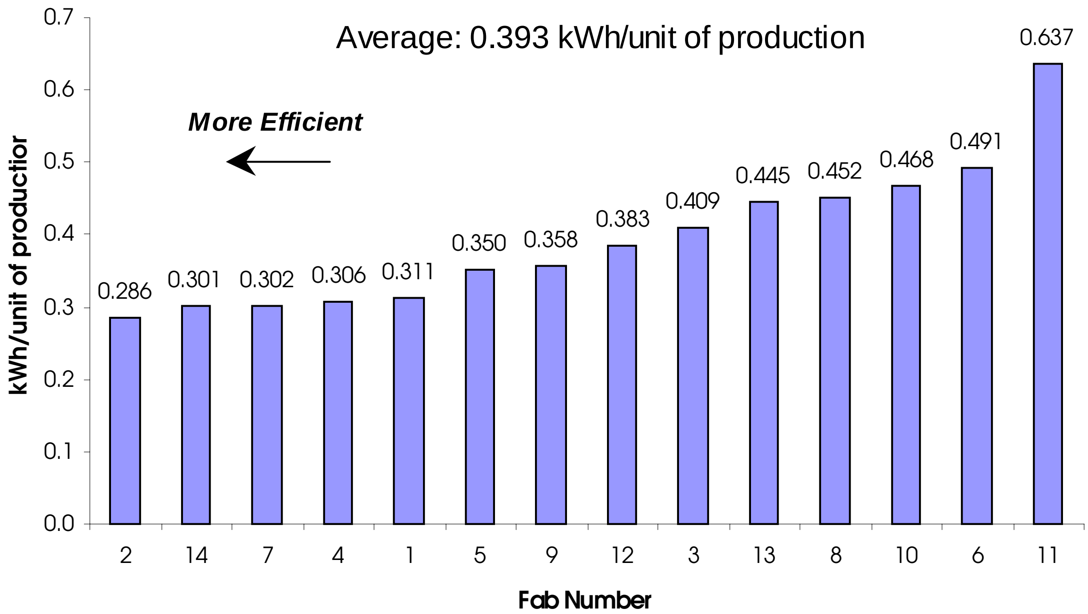


Figure 3-4
Electrical Utilization Index

The three most efficient fabs in terms of the electrical utilization index were fabs 2, 14, and 7. Fabs 2 and 7 are located in Asia; fab 14 is located in the United States. Fab 2 is 3 years old, and fabs 7 and 14 are 7 years old.

The fab with lowest overall electricity use per unit of production, fab 2, is located in a hot and humid tropical environment with an average annual temperature of 72°F (22°C). This fab also was among the most efficient or in the lowest-consuming half of the participants for almost all of the facility systems and subsystems reported. Cooling loads at this fab would be expected to drive up the total energy consumption of the fab, but this is not the case with fab 2. As can be seen later, fab 2 runs one of the most efficient chiller systems despite its atypically warm climate.

The fab with the next lowest electrical utilization index, fab 14, is located in a temperate and humid climate with an average annual temperature of 53°F (12°C). This fab may have seasonal gas heating loads that are not included in this analysis (this analysis covers only electrical loads). The fab appears to perform at or near average in all measurements except the central cooling plant use, which is significantly below average.

Fab 7 has the third most efficient electrical utilization index. This fab is located in a hot, humid climate in Asia where the average annual temperature is 81°F (27°C)—the hottest of all average temperatures reported.

The calculated values of total fab electricity usage per unit of production did not display any apparent correlation to average annual temperature (shown in Figure 3-5).

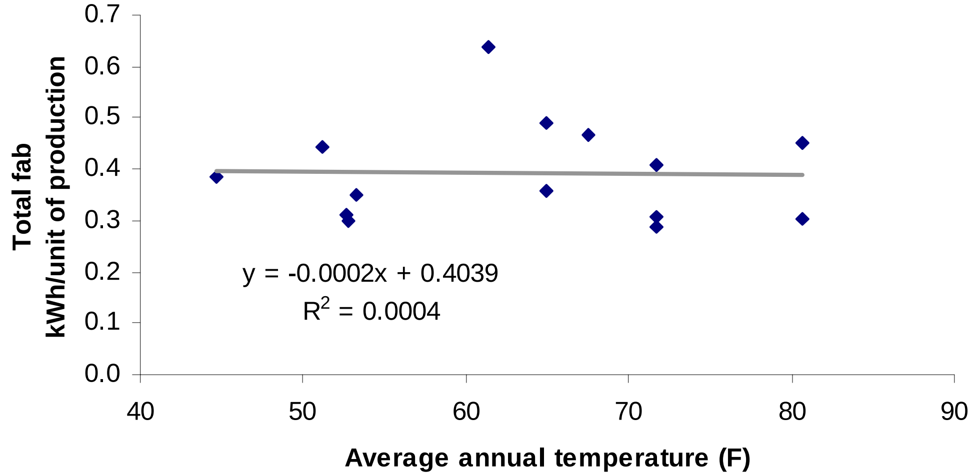


Figure 3-5
Relationship Between Average Annual Temperature and Total Fab Electricity Usage per Unit of Production

Separate analysis of the cooling load does show limited weather dependence, as will be discussed later.[8] The major difference in energy use appears to be in lower energy usage in the central utility services such as the central chiller plant, nitrogen, and UPW systems. These factors could place a facility that is more efficiently using its resources at a higher overall energy consumption level than a less efficient facility.

Production Efficiency Index

Energy efficiency can also be analyzed in terms of electricity usage per square inch (or square centimeter) of silicon processed per year. This value, defined as the production efficiency index, relates directly to energy efficiency goals specified in the Semiconductor Industry Association *National Technology Roadmap for Semiconductors*. This metric is commonly used in the semiconductor industry in the United States. The production efficiency index is equivalent to the electrical utilization index, except the production efficiency index does not take the average number of mask layers into account. It therefore normalizes energy efficiency by the wafer area output of the fab, but does not take into consideration the manufacturing complexity of the wafer product. The production efficiency index for the 14 fabs studied is shown in Figure 3-6.

[8] Scatter plots showing the relationship between total fab kWh/unit of production, chiller plant kWh/unit of production, and average annual temperature are presented in Appendix G, Additional Scatter Plots and Bar Charts.

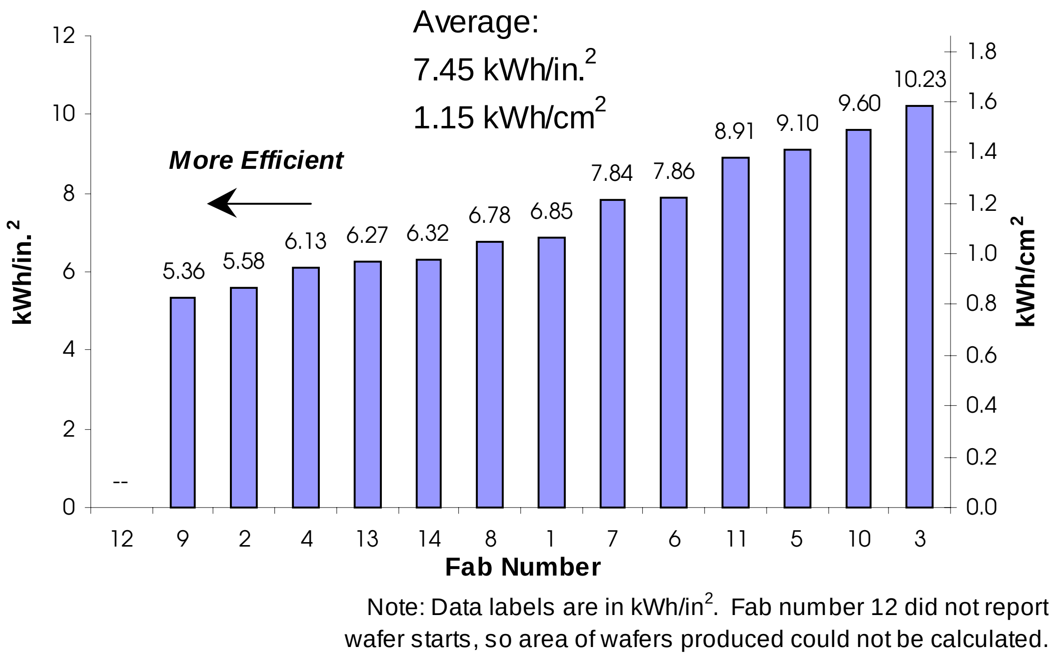


Figure 3-6
Production Efficiency Index

The average value of the production efficiency index was 7.45 kWh per square inch (1.15 kWh per square centimeter); values ranged from a high of 10.23 kWh per square inch to a low of 5.36 kWh per square inch (1.59 to 0.83 kWh/cm^2).

The top fabs in terms of the production efficiency index were fabs 9, 2, and 4. Fab 9 is located in the United States, while fabs 2 and 4 are located in Asia. Fab 9 reported the second highest number of wafer starts per year (564,000) of all the fabs studied; however, this high throughput is tempered by the fact that the fab processes 150 mm wafers instead of larger 200 mm wafers. Fab 9 is 14 years old.

Fab 2, which reported the highest number of wafer starts per year (775,824), uses 200 mm wafers in its production process. Fab 2 is 3 years old.

Fab 4 is also 3 years old. Only three fabs reported a lower number of wafer starts per year than fab 4, which also uses 200 mm wafers in its production process; it was also the smallest fab in terms of production floor area. This fab demonstrates that energy economies of scale are not necessarily a certainty in fabs—even a small fab with lower than average throughput can be among the most energy efficient when normalized for production.

Tool Production Index

The aggregate electrical load of a fab's process tools is the largest electrical load in a typical fab, accounting for an average of 40.7% of all energy consumed by fabs participating this study. Aggregate tool load can usually be metered with native electrical load monitoring stations if the electrical buses for tools are separate from the facility loads. This is usually the case in newer fabs and the accuracy of the metered data for aggregate tools should be very high in these facilities.

In older facilities, loads tend to be mixed together at the electrical distribution panel, and technicians may have a more difficult time obtaining accurate tool load data. Tool loads tend to be constant relative to other loads in the fab. Individual tools may have a high variability in electrical consumption over time, but when combined with all the other operating tools within a fab the result is a relatively uniform load.

The annual tool electrical consumption per unit of production is defined as the tool production index (see Figure 3-7). The average value for the tool production index was 0.137 kWh per unit of production.

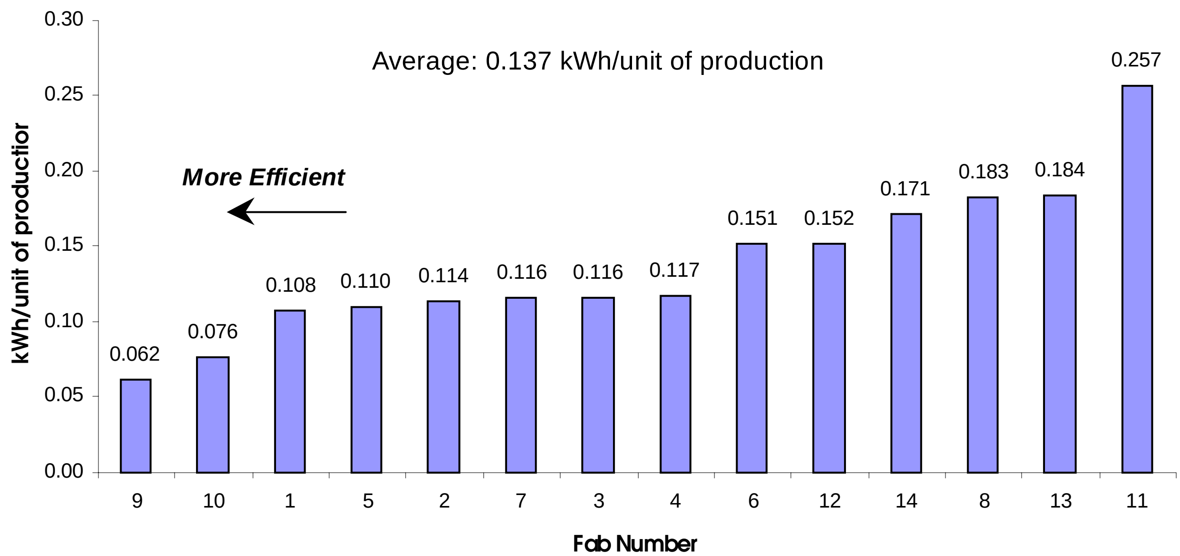


Figure 3-7
Tool Production Index

The top three fabs in terms of the tool production index are fabs 9, 10, and 1. Fabs 9 and 10 are located in the United States; they are 14 and 3 years old, respectively. Fab 1 is located in Europe; it is five years old.[9]

Summary of Top Performing Fabs

Table 3-2 identifies and ranks the top three fabs by each performance index and shows which fabs were among the top three performers in multiple indices.

[9] The reported age of fab 9 is 14 years, but this fab has had several retrofits since it began operating.

Table 3-2
Top Three Fabs by Each Performance Index

Performance Index	Fab Number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Production Index (total fab units of production)		1			2							3		
Space Utilization Index (units of production/production floor area)				1	2					3				
Electrical Utilization Index (total fab kWh/unit of production)		1					3							2
Production Efficiency Index (total fab kWh/square inch of wafer processed)		2		3					1					
Tool Production Index (kWh of process tools/unit of production)	3								1	2				

Only one fab was among the top three fabs surveyed in three of the five indices of performance. This was fab 2, which was the top performing fab in the production and electrical utilization indices and the second highest performing fab in the production efficiency index. Fab 2 uses 200 mm wafers in its production processes. It is three years old and is located in Asia. Its cleanroom is of a ballroom design with minienvironments.

Four fabs were among the top three fabs surveyed in two of the four indices of performance. These were fabs 4, 5, 9, and 10. Fab 4 was among the top performers in the space utilization and production efficiency indices, fab 5 was among the top performers in the production and space utilization indices, fab 9 was among the top performers in the production efficiency and tool production indices, and fab 10 was among the top performers in the space utilization and tool production indices. Fabs 4, 5, and 10 use 200 mm wafers in their production process; they are 3 years old. Fab 9 uses 150 mm wafers; it is 14 years old. Fabs 9 and 10 are located in the United States; fabs 4 and 5 are located in Asia. Two of the fabs are of a ballroom design; the other two have both ballroom and bay and chase design elements.

Four other fabs were among the top three fabs in only one index of fab performance. These were fabs 1, 7, 12, and 14. Two of these fabs are located in Asia and two are located in the United States. Fab 1 located in Europe is 5 years old. Fabs 12 and 14 in the United States are 15 and 7 years old, respectively. Fab 7 in Asia is 7 years old. Three of these fabs are of ballroom design; the other, fab 12, has both ballroom and bay and chase design elements.

Energy Use by Facility Systems

This section reviews energy usage by facility systems, presents site-specific information for each facility system and subsystem, discusses significant data trends relating to each system or subsystem, and summarizes significant conclusions that result from the data.

Facilities data include all the major facilities systems found in a fab:

- Central plant/chillers
- Makeup air
- Recirculating air
- Exhaust air
- Nitrogen
- Compressed dry air
- Process cooling water
- UPW

Data for each of these facilities systems are presented in a summary table and in two bar charts. The first bar chart shows the energy efficiency of the systems in general, represented as units of generation divided by the unit of energy required, such as cfm (cmh) or gpm (lps) per kW of electricity. This format allows easy comparison of operating efficiency from system to system. The second type of bar chart is energy usage by the system normalized by units of production. This metric allows for easy comparison of energy usage from fab to fab. The units of this metric are always kilowatt-hours per unit of production.

The description of facilities systems data concludes with more detailed discussion and analysis of top performing systems using data gathered in the final phase of this project. After top performing fabs were identified, the project consultant conducted follow-up surveys and interviews with at least three fabs in each facilities system category to collect more detailed information on the systems, to understand the data collection methodology that was used, to verify that submitted data were accurate, and to postulate explanations of the systems' relatively high performance.

Central Plant/Chillers

Description

The central plant includes the chillers and their support systems. Central plant data includes the energy used for operating the facility or the portion of the facility that houses the central plant. Some of the facilities studied in this project had the central plant equipment in unconditioned structures while others had designed temperature and humidity controlled structures. These design features can affect the overall energy requirements and cost of cooling the fab. General parameters of the central plants of participating fabs are presented in Table 3-3.

Table 3-3
Central Plant Data

Fab Number	**Chillers**			**Tower Cooling**			**Chilled Water System Auxiliaries**	**Chiller Plant Building Systems**			**Heating Water System**			
	Average Measured Electric Load	Average Cooling Output		Average Measured Electric Load	Average Cooling Output		Average Measured Electric Load	Measured Average Building Electric Load	Annual Building Cooling Load		Type of System	Measured Average Boiler Energy Input	Measured Average System Auxiliaries	Average Boiler Operating Efficiency
	(kW)	(tons of refrig.)	(kW)	(kW)	(tons of refrig.)	(kW)	(kW)	(kW)	(ton-hrs of refrig.)	(kWh)	hot water (HW), high temperature (HT) or steam (ST)	(MMBtu/hr)	pumps, fans (kW)	(%)
1	2,495	2,560	9,000	350			550				HW	12	50	92%
2	5,867	9,000	31,644	175			520				HW	60	152	95%
3	3,082	3,602	12,665	164	4,404	15,484	789	100	700,800	2,463,991	HW		50	
4	2,009	2,869	10,087				631	11			HW	5	40	90%
5	2,798	3,308	11,631	130			1,624				Steam	36	25	85%
6	2,145	2,860	10,056	101	3,470	12,200	862	57	450,000	1,582,186	HW	2	52	0%
7	1,720	2,716	9,551	161	2,716	9,551	492	53	217,248	763,837	HW/steam		25	85% / 98%
8	3,200	4,629	16,275	164	5,500	19,338	375	14	595,680	2,094,392	HW	10	9	83%
9	2,484	3,750	13,185	116	4,500	15,822	484	170	180,000	632,874	HW & Steam	7	180	80%
10	3,664	5,731	20,150	206	6,300	22,151	881	70	300,000	1,054,791	HW	9	100	82%
11	3,000	5,000	17,580	500	5,000	17,580	250				HTHW & steam	18	100	
12	1,965	2,370	8,333	246	2,930	10,302	246	2			HTHW	44	127	83%
13	380	597	2,099					412	1,023,900	3,600,000	HTHW	31	See Boiler	80%
14	1,442	1,620	5,696	60			375				HW	23	172	83%

Note: Blank cells and zeros indicate data not reported. Data appears as reported by the respondent.

Fab cooling requirements vary seasonally. The best method for annual cooling load assessment is to collect metered load data for a complete year or multiple years. Some fabs have this data available, but most do not. Fabs where annual metered load data were not available were asked to predict the average loads using standard load modeling techniques. In all cases, the survey team at each fab was responsible for providing the annual average cooling loads of the facility and the hours of cooling system operation.

Heating loads were collected in the same manner as cooling loads. Participants submitted the average heating load and the number of hours per year that the heating system was operational.

Results

Chiller subsystem loads submitted by four of the fabs totaled more than the total output of the central chiller plant, and loads submitted by nine fabs totaled less than the central plant output. Fab 14 submitted loads that matched the plant output but not all loads for the fab were submitted. Based on this review of the submitted data, the reported distribution of the cooling load is not accurate, but the aggregate cooling load data is more accurate.

Chiller plant efficiency was calculated as the total amount of electricity into the chiller system (in kW, including all balance of plant equipment) divided by the tons of chiller output. These values are presented below in Figure 3-8. Many of the data points provided by the participants for plant efficiency were in the expected range of 0.6 to 1.0 kW/ton. Fabs 11 and 2 reported chiller plant efficiencies of 0.65 and 0.71 kW/ton, which are extremely high for these systems. These fabs did not report energy for the entire central plant facility, but did include data on pumps and cooling towers, a subset of their central plants.

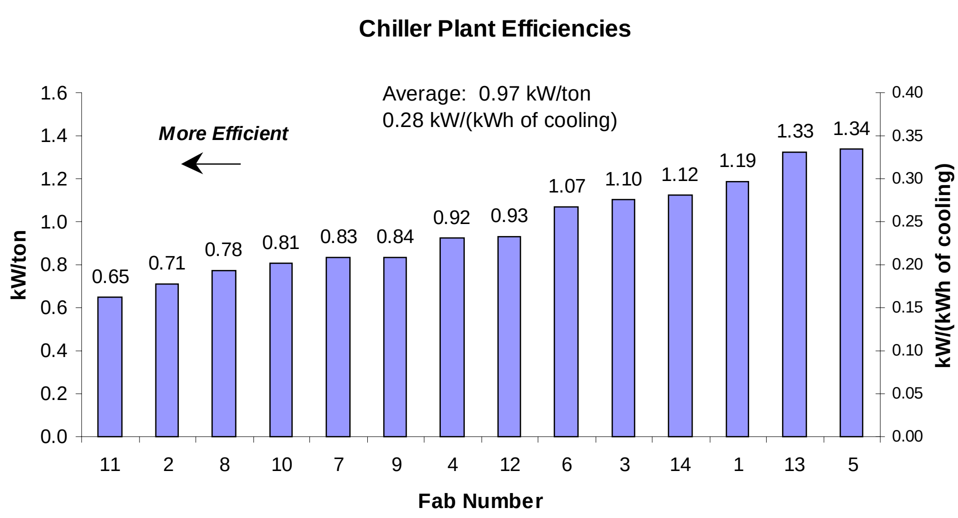


Figure 3-8
Chiller Plant Efficiencies[10]

[10] Reported chiller plant data is comprehensive and includes balance of plant equipment.

The average normalized energy usage for operating a central cooling plant was 0.100 kWh per unit of production as shown in Figure 3-9. The average value for this metric was 0.100 kWh per unit of production, with values falling in the range of 0.054 to 0.163 kWh per unit of production.

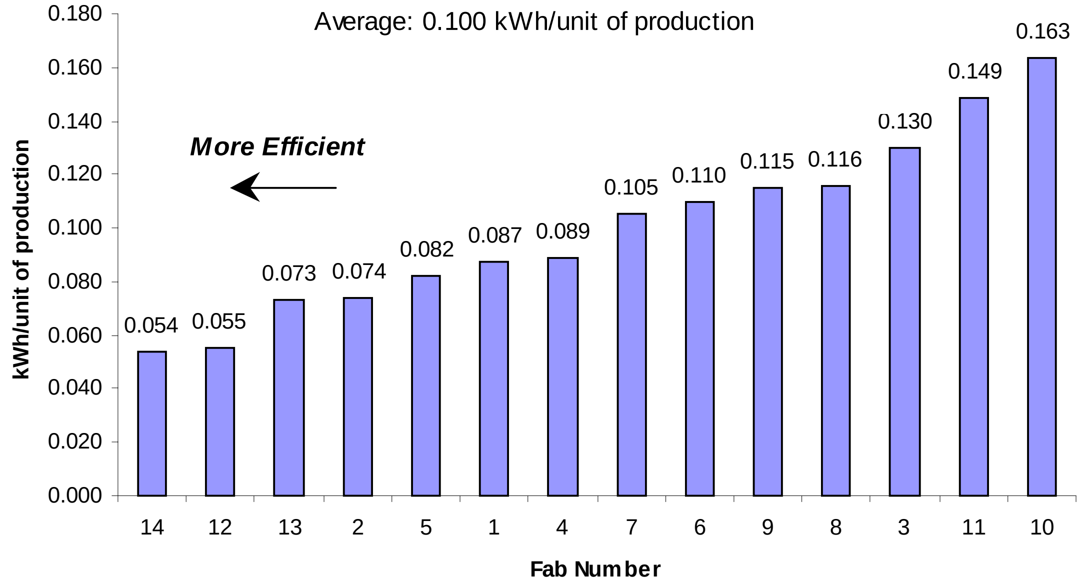


Figure 3-9
Annual Energy Usage by Chillers Normalized by Units of Production

The energy usage per fab tended to follow the local climate conditions, with lower usage for colder climates and higher usage for warmer climates.

A scatter plot comparing chiller plant kWh/unit of production against average annual temperature appears in Figure 3-10. It shows a relationship between chiller plant efficiency and climate, but the relationship is not strong in a statistical sense because of the small sample size.

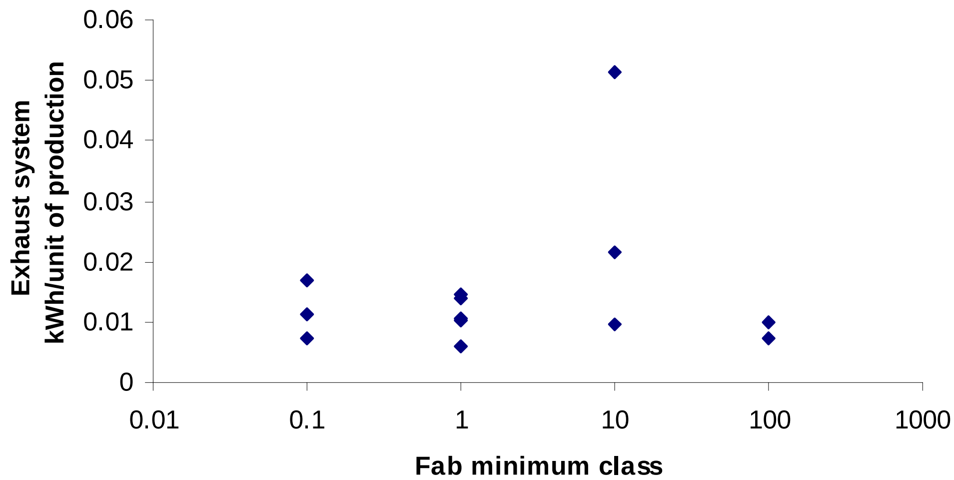


Figure 3-10
Relationship Between Chiller Plant Energy Efficiency and Average Annual Temperature

Two exceptions did occur. Fab 2, located in a hot, humid climate, had one of the lowest normalized energy usage for the central plant, while another fab, fab 11, located in a mild climate, had one of the highest normalized energy efficiencies. Interestingly, while chiller systems of fabs 13 and 14 were among the most efficient in the kWh per unit of production analysis, these chiller systems were among the least efficient in terms of the kW per ton analysis. This finding is especially confounding since fab 13 reported the lowest production of any fab in the study (this would tend to make its kWh/unit of production figure higher, or more inefficient).

Chiller Systems Top Performers—Detailed System Information and Best Practices

Fab 14

- **System Description**

Fab 14's chillers demand an average 1,442 kW of electricity and produce 1,620 tons of cooling output. The tower cooling system has an averaged measured electrical load of 60 kW; cooling output was not recorded. The chilled water system auxiliary pumps demand an average 375 kW of electricity. The average measured electric load and cooling load of the chiller plant building systems was not reported. The heating water system is a hot water system with a measured average boiler energy input of 23 MMBtu per hour; the system auxiliaries (pumps, fans, etc.) have an average electrical demand of 172 kW. The boiler operates at 83% efficiency.

The system is also equipped with two glycol chillers with an efficiency estimated at 1.0 kW/ton. The chillers are used for the final dehumidification stage in the makeup air system. The facility is of ballroom design and does not have separate enclosures for photo or other process areas with differing environmental conditions.

The chiller plant uses a traditional primary/secondary piping system. The primary system consists of chillers in parallel with constant volume pumps dedicated to the chillers. The secondary system is a variable volume pumping system. There is no traditional tertiary loop; however, a few areas have been added onto the system that require additional pumps to maintain flow.

The supply and return water temperatures are 42 and 54°F (6 and 12°C), respectively. This results in 12°F (-11°C) differential across the system, which is very high for a fab and would contribute to lower secondary pumping loads. The system is equipped with five centrifugal water chillers with an efficiency in the range of 0.57 to 0.60 kW/ton. Two of the chillers are heat recovery type chillers; heat from the condensers on these units is used to provide heating for the UPW system.

The chiller sequencing control is unusual; it is based upon chiller head pressure. The site is not equipped with any form of cooling recovery, including tower water cooling. The makeup air unit discharge air temperatures are controlled at a constant 69°F (21°C) and do not vary with fab conditions. The same chiller plant provides cooling to the makeup air systems and the recirculating fan systems.

The cooling towers are dedicated to the chillers and start when a chiller is started. The towers have two-speed fans; they are controlled to maintain 85°F (29°C) condenser water supply temperature.

All the pump and tower fan motors are high-efficiency. The secondary piping system uses less than 50% of the installed pump capacity annually.

- **Data Collection Methodology**

Chiller plant performance was obtained from the monitoring system installed in the fab; the date of the last calibration was unavailable. The system performance data were obtained from kW metering and intrusive flow metering equipment.

- **Conclusions**

According to fab engineering staff, the most likely reason for the high efficiency of the chiller plant is climate. The only significant performance upgrade that has been installed in the past few years are control system modifications. At the time of this study, this fab was improving its tower control and heat recovery chiller control and needed to modify the glycol chiller control to keep units from unstable operation. The new control system provides chiller sequencing control based upon chiller head pressure. This is an unusual control variable. More specific information on its operation is not available.

The plant does not appear to be abnormal in any areas other than perhaps a higher than average differential across the chilled water system. The most apparent reason for the low energy use of the plant is climate related. The plant itself is one of the least efficient plants in the survey; its low cooling usage boosted the plant to the level of top performers.

Fab 12

- **System Description**

Fab 12’s chillers demand an average 1,965 kW of electricity and produce 2,370 tons of cooling output. The tower cooling system has an average measured electrical load of 246 kW and produces 2,930 tons of cooling output. The chilled water system auxiliary pumps average electrical demand of 246 kW of electricity. The chiller plant building systems have an average measured electric load of 2 kW; cooling load was unreported. The heating water system is a high temperature hot water system with a measured average boiler energy input of 44 MMBtu per hour; the system auxiliaries (pumps, fans, etc.) have an average electrical demand of 127 kW. The boiler operates at 83% efficiency.

The fab’s primary piping loop accounts for 100% of the total chiller system load. The average supply temperature is 42°F (6°C), and the average return temperature is 52°F (11°C). The primary piping loop uses variable flow, and the pumps use variable frequency drives and high efficiency motors.

Chiller sequencing is controlled with a control system based on pressure changes, most of which is automatic. High efficiency motors are used to power chilled water distribution pumps and condenser pumps. The plant does not use thermal energy storage or any other innovative cooling technologies. The makeup air unit discharge air temperature and dew point are constant. There are separate chiller systems and separate makeup air systems used for photo dehumidification. There is also a separate makeup air system used for chemical mechanical polishing. The chillers and pumps are located in conditioned space.

The tower sequencing for the condenser water system is automatic. The towers are not used for free cooling applications.

- **Data Collection Methodology**

Further information on this fab’s data collection methodology was not available.

- **Conclusions**

Facility engineering staff believe that the fab has performed well in this area because of the installation of variable speed drives on the majority of motors in the chiller system. This fab does not have one central chilled water plant, but is a series of smaller chilled water plants that have been tied together as part of an ongoing retrofit process. The facility staff have written a custom program for controlling the system to obtain the best efficiency while meeting the facility loads. Nevertheless, the distributed nature of this system has resulted in higher pump energy that, coupled with the high efficiency chillers, results in only average overall performance for this plant. The fab excels at low energy use for cooling, which is primarily a result of the cold local climate.

Fab 2

- **System Description**

Fab 2's chillers demand an average 5,867 kW of electricity and produce 9,000 tons of cooling output. The tower cooling system has an average measured electrical load of 175 kW; cooling output was not recorded. The chilled water system auxiliary pumps demand an average 520 kW of electricity. The average measured electric load and cooling load of the chiller plant building systems was not reported. The heating water system is a hot water system with a measured average boiler energy input of 60 MMBtu per hour; the system auxiliaries (pumps, fans, etc.) have an average electrical demand of 152 kW. The boiler operates at 95% efficiency.

The chilled water plant layout is composed of two primary/secondary loop systems with the chillers piped in parallel. The primary and secondary piping loops have average supply temperatures of 41°F and 48°F (5°C and 9°C) and average return temperatures of 50°F and 56°F (9.8°C and 13.6°C), respectively. The design of the primary loop pumps is 0.043 hp per ton (0.032 kW per ton). Actual operation of the pumps is 0.047 hp per ton (0.035 kW per ton). For the primary loop, high efficiency motors are used, but the pumps do not have variable frequency drives. For the secondary loop, high efficiency motors and variable frequency drives are used. The secondary piping system is variable flow. The 48°F (9°C) chillers have an efficiency of 0.557 kW/ton and the 41°F (5°C) chillers have an efficiency of 0.699 kW/ton.

The chiller sequencing procedure is automatic, depending on system supply temperature and chiller loading. Each chiller has its own chilled water distribution pump that is also automated. High efficiency motors are used system-wide to power chilled water distribution pumps, condenser pumps, and cooling tower fans. The chiller plant does not use thermal energy storage or any other innovative cooling technologies.

The condenser water pumps and tower sequencing procedures are also automated.

- **Data Collection Methodology**

The chiller systems were trend-metered by portable instrumentation over a 24-hour period. The chiller plant was metered in groups of chillers: primary chilled water pumps, secondary chilled water pumps, and cooling towers. The results were used to predict the annual energy consumption of the plant.

- **Conclusions**

Facility engineering staff believe that their fab performed well in this category because it is a newer fab, it uses new design concepts, and it has good management. The fab engineering staff designed its own software to automate chiller plant equipment, making operation more efficient.

The chiller plant configuration is typical of most fabs except for the two temperature loops, which only a few fabs have implemented. The dual temperature loops produce higher temperature water more efficiently than the water chiller systems can produce lower temperature water. The efficiency of the chillers is fairly typical of new, state-of-the-art units and is significantly higher than those found in the older fabs.

The chiller system excels primarily in pure efficiency of generation with the lowest aggregate kW/ton of all the plants in the survey. The system was also below average in cooling requirement, which is quite an accomplishment for a fab located in a hot and humid environment. The reduced cooling load results from high system efficiency in most of the other facilities systems in the fab.

This fab has implemented a comprehensive effort to minimize exfiltration from the fab. Fab engineering staff point out this effort as a likely contributor to this facility's high performance in the makeup air system category, but it also may contribute to lowering the cooling load in the work environment, improving the efficiency of the central plant/chiller system.

Makeup Air System

Description

Makeup air systems are used to condition all outdoor air before it enters the fab. Conditioning includes dehumidification, cooling, heating, and, in many fabs, filtration to remove particulates. All fabs are maintained at a positive pressure to prevent infiltration of particulates and other contaminants into the cleanroom space. Many different design methods have been used on the outdoor air systems to increase efficiency. The primary conditions affecting the systems are the static pressure differential of the fan system, fan efficiency, and quantity of makeup air. General data about the makeup air systems of participating fabs are presented in Table 3-4.

Table 3-4
Makeup Air Systems Data

Fab Number	General Data	Air Handling Unit Data										
	Variable Flow	Number of units	Average measured electric load	Average Flow		Discharge Temperature Setpoint		Discharge Temperature Setpoint		Average Annual Cooling Load		Air Changes per Hour[1]
			(all operating units) kW	CFM	CMH	(wet bulb) F	(wet bulb) C	(dry bulb) F	(dry bulb) C	(ton-hours of refrig)	(kWh)	
1	Yes	7	175	200,226	340,004	70	21	57	14	3,077,000	10,818,635	216
2	Yes	16	430	55,969	95,041	58	15	72	22	0		64
3	Yes	10	305	275,935	468,565	55	13	66	19			154
4	Yes	6	93	187,273	318,008	Summer 49 / Winter 55	Summer 10 / Winter 13	Summer 50 / Winter 62	Summer 10 / Winter 17	7,499,385	26,367,600	225
5	Yes	7	322	228,964	388,804			55	13	310 RT		176
6	Yes	8	157	160,000	271,696	42	6	53	12	5,703,000	20,051,568	170
7	Yes	5	210	166,953	283,503	55	13	65	19	7,920,904	27,849,648	63
8	Yes	VSD	201	240,683	408,705	51	11	55	13	19,149,592	67,329,360	47
9	Yes	2	249	175,500	298,017	41	5	52	11	6,475,322	22,767,027	67
10	Yes	11	109	166,000	281,885	42	6	68	20	2,531,640	8,901,166	185
11	No	26	1,360	1,040,000	1,766,024	41	5	41	5			384
12	Yes	14	1,188	712,000	1,209,047	42	6	Summer 46 / Winter 57	Summer 8 / Winter 14	875	3,076	51
13	No	14	158	94,224	160,002	54	12	57	14	1,137,667	4,000,001	166
14	Yes	5	224	257,000	436,412	45	7	70	21	1,100	3,868	100

[1] Assumes fab ceiling height of 15 feet.

Note: Blank cells indicate data not submitted. Data appears as reported by respondent.

Results

Makeup air handling units operate throughout the year, 24 hours per day. The fan motors alone use an average of 2.9% of the total electric energy in a fab. In addition to the energy load supplied directly to the fans, the electrical motor usage may increase the cooling load of the units. Energy data collected on makeup air handler fans indicate that the efficiency of the systems (as indicated by the average measured flow air rate divided by the average measured electrical demand) varies significantly from the average value of 946 cfm/kW (1,606 cmh/kW). Fab 4 reported the most efficient system, with an efficiency of 2,007 cfm/kW (3,408 cmh/kW), while fab 2 reported the least efficient system, with an efficiency of 130 cfm/kW (221 cmh/kW). Figure 3-11 shows the makeup air unit fan efficiency of each of the 14 participating fabs.

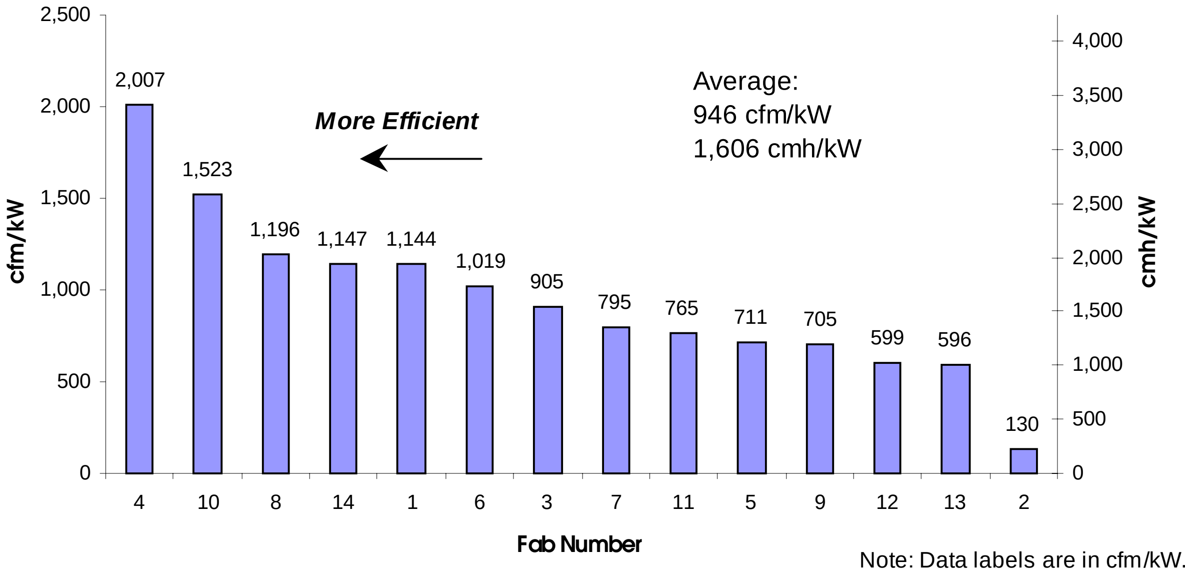


Figure 3-11
Makeup Air Unit Fan Efficiencies

When efficiency is normalized by units of production, the results are similar, but with one notable exception. Fab 2 registered the lowest efficiency level in Figure 3-11, but it jumped to the third best efficiency level in terms of kWh per unit of production. The makeup air systems have a normalized average value of 0.013 kWh per unit of production (see Figure 3-12).

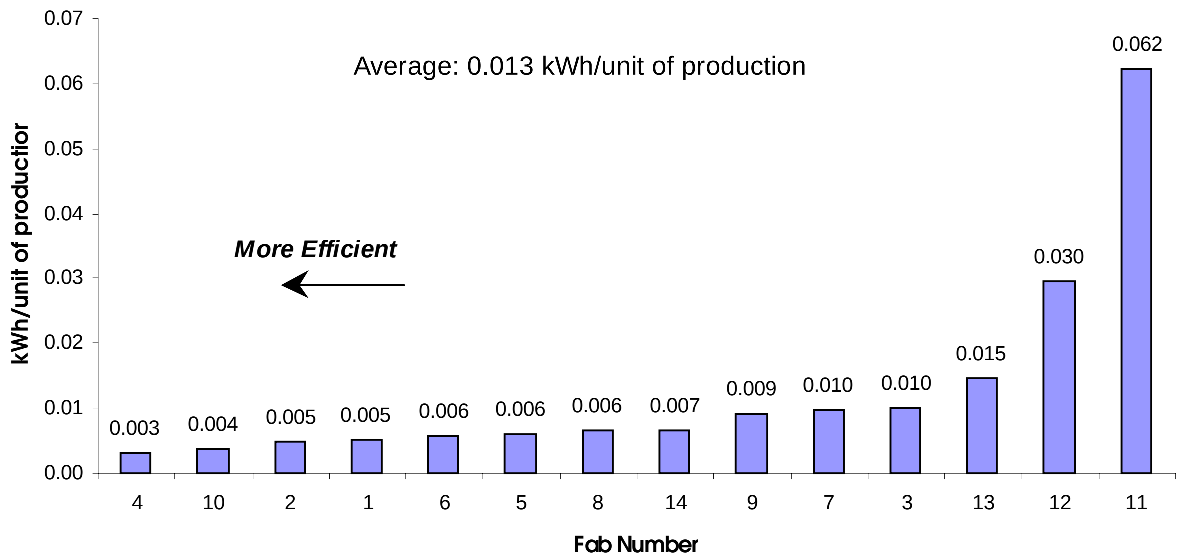


Figure 3-12
Annual Makeup Air System Energy Use Normalized by Units of Production

Fabs 4 and 10 are still the two most efficient makeup air systems by this metric, but fab 2's ranking increases from the least efficient system to the third best system overall. This indicates that fab 2's makeup air fans are relatively inefficient when compared with those of other fabs, but that its large production index (fab 2 reported more wafer starts and more units of production than any other fab) makes up for the inefficiency of the system. It is worth noting that fabs 2 and 8 were the only fabs in the study group that incorporate minienvironments in their design. Since minienvironment loads are counted as tool loads, the minienvironments could decrease the load on both the makeup air and recirculating air systems. This could explain its high normalized efficiency level.

Makeup Air Systems Top Performers—Detailed System Information and Best Practices

Fab 4

- **System Description**

Fab 4's makeup air system uses six variable flow air handling units with an average measured electric load of 93 kW and an average air flow of 187,273 cfm (318,008 cmh). The wet bulb discharge temperature setpoint is 49°F (10°C) in the summer and 55°F (13°C) in the winter; the dry bulb discharge temperature setpoint is 50°F (10°C) in the summer and 62°F (17°C) in the winter. Average annual cooling load is about 7.5 million ton-hours of cooling.

The volume of the pressurized portion of the fab is 6500 ft^2 (26,502 m^3). The air flow per fan is 37,101 cfm (63,000 cmh), compared to the design air flow of 58,890 cfm (100,000 cmh). The actual fan static pressure in the makeup air unit is 500 Pascals (2.01 in. H_2O), compared to the design static pressure of 650 Pascals (2.61 in. H_2O). The fan design efficiency rating is 86%. The high efficiency particulate air (HEPA) filters in the system have a design pressure drop of 230 Pascals (0.92 in. H_2O) across the filter. High efficiency motors and variable frequency drives are used in the makeup air system.

The actual pressure drop across the HEPA filters is only 80 to 140 Pascals (0.32 to 0.56 in. H_2O), and the makeup air fan motor inverters are operating at 35 Hertz, rather than the standard 60 Hertz. Since air flow is directly proportional to fan speed, it appears that the system is oversized by 71% (60 Hertz/35 Hertz).

- **Data Collection Methodology**

The data were collected with portable spot and trend meters. Metering equipment is calibrated annually.

- **Conclusions**

Facility engineering staff believe that fab 4 performed well in this area because the fab is designed more efficiently; has better operations management; and uses more efficient motors, filters, and other accessories. Specifically, fab staff attribute the system's efficiency to the following:

- Low pressure drop filters are used, saving on power consumption.
- The best air supply condition set point is selected, saving chilled water, hot water, and DI water consumption.
- The best makeup air running units have variable speed drives, saving power consumption.
- The outside air supply (reduced exhaust and room leakage) is suitable, saving power and HVAC consumption.
- The supply air chamber pressure is reduced, saving power consumption.

The makeup air systems had one of the highest efficiencies and lowest supply volumes per unit of production of sites surveyed. The makeup air quantity is only 4% higher then the exhaust quantity, which indicates an extremely tight facility from a leakage standpoint.

Fab 10

- **System Description**

Fab 10's makeup air system uses 11 variable flow air handling units with an average measured electric load of 109 kW and an average air flow of 166,000 cfm (281,885 cmh). The wet bulb discharge temperature setpoint is 42°F (6°C); the dry bulb discharge temperature setpoint is 68°F (20°C). Average annual cooling load is about 2.5 million ton-hours of cooling.

The makeup air handlers fall into four categories depending on some combination of the units' configuration or the area served. Only the units serving the production levels use glycol cooling coils, where extreme dew point control is required. Only the production level units have humidifiers; they are run continuously for final conditioning of the air before reheating.

Approximately 3,709 tons of chilled water and 176 tons of glycol cooling capacity with a total buildout of some 6,800 tons of chilled water and 343 tons of glycol constitute nearly 30% of this facility's connected load. The continuous operation at high load conditions increases the likelihood of their energy consumption being at least that high.

- **Data Collection Methodology**

The data for this fab were not originally metered for this survey and were adapted from a previous survey. The original survey metered the energy use for the fab but only one- half of the fab was in production. As a result, many of the systems were oversized for the actual load at the time, but would not maintain the same efficiency level when the entire fab was populated with tools and placed in operation.

- **Conclusions**

The makeup air system results are a combination of high efficiency systems and additional efficiency because of the partial operation of the fab. Actual energy use was allocated between the operating portion of the fab and the non-operating portion of the fab, but the impacts of a dramatic increase in total load on the support systems as fab production increased was not included in the measured values.

Fab 2

- **System Description**

Fab 2's makeup air system uses 16 variable flow air handling units with an average measured electric load of 430 kW and design air flow of 55,969 cfm (95,041 cmh). The wet bulb discharge temperature setpoint is 58°F (15°C); the dry bulb setpoint is 72°F (22°C). Average annual cooling load was not reported.

The volume of the pressurized portion of the fab is 125,800 ft^3 (3,560 m^3). The actual air flow per fan is 39,120 cfm (66,430 cmh) compared to the design air flow of 55,890 cfm (94,907 cmh). The actual fan static pressure in the makeup air unit is 1,866 Pascals (7.5 in. H_2O) compared to the design static pressure of 2,687 Pascals (10.8 in. H_2O). The fan design efficiency rating is 82%. The system has HEPA filters with a design pressure drop across the filter of 260 Pascals (1.05 in. H_2O). The makeup air system uses high efficiency motors and variable frequency drives.

- **Data Collection Methodology**

The metering for both the electrical and flow measurements was performed with high quality portable instrumentation. However, the air flow, static pressure, and fan efficiency combination appear to indicate a higher fan energy use than measured. Of the measurements in this category, fan flow rate is the hardest to measure accurately and would be the most suspect of the measurements. There also is a difference in the construction of the makeup air system in two fabs at this facility site that could cause discrepancies in the static pressure reading between the systems that would not be represented by the single static pressure reading requested for the system. If there is an inaccuracy in the measurements, it is probably in overestimating the air flow or the static pressure.

- **Conclusions**

Facility staff at fab 2 believe that the fab performed well in this area because of its new design concept, which involves a class 1 minienvironment and a class 100 ballroom. The ballroom provides more space for equipment. The air leakage from the cleanroom has been improved, reducing the fan speed/volume of the system by 2%.

The fan efficiency appears to be a contributor in the overall system efficiency and the low makeup air volume is the other key contributor. The fan volume and static pressure may be overstated or the fan electrical load may be understated because the combination is higher than predicted with a standard fan load calculation. The fan static pressure of 1,866 Pascals (7.5 in. H_2O) appears slightly high for a high efficiency unit and may only apply to one of the two fabs at this site which discharges into the recirculating unit discharge. The other fab’s makeup air units discharge into the recirculating unit return air plenum.

Each fan is equipped with four coils and the HEPA pressure drop is slightly more than 248 Pascals (1 in. H_2O). The fan discharges into the suction of the recirculating fans. Fab pressurization is average to high for similar fabs, but the makeup air volume is low. The fab has implemented a comprehensive program to seal any air leaks between the fab and outside areas.

Recirculating Air System

Description

Cleanroom space conditioning is provided by the combination of makeup air units and recirculating fan systems. There are multiple design philosophies for the recirculation systems and three primary types of systems.

The system that is probably in widest use throughout fabs is the fan tower unit (FTU), also called a vertical laminar flow (VLF) unit. These units consist of a fan and a sensible cooling coil that typically supplies cool air to a plenum above the cleanroom. The floor or the ceiling of the cleanroom is a combination of ceiling tiles and HEPA filters. Air passes through the filter into the cleanroom and returns to the FTUs, either at floor level or through the sub-fab below the main fab floor (see Figure 3-13).

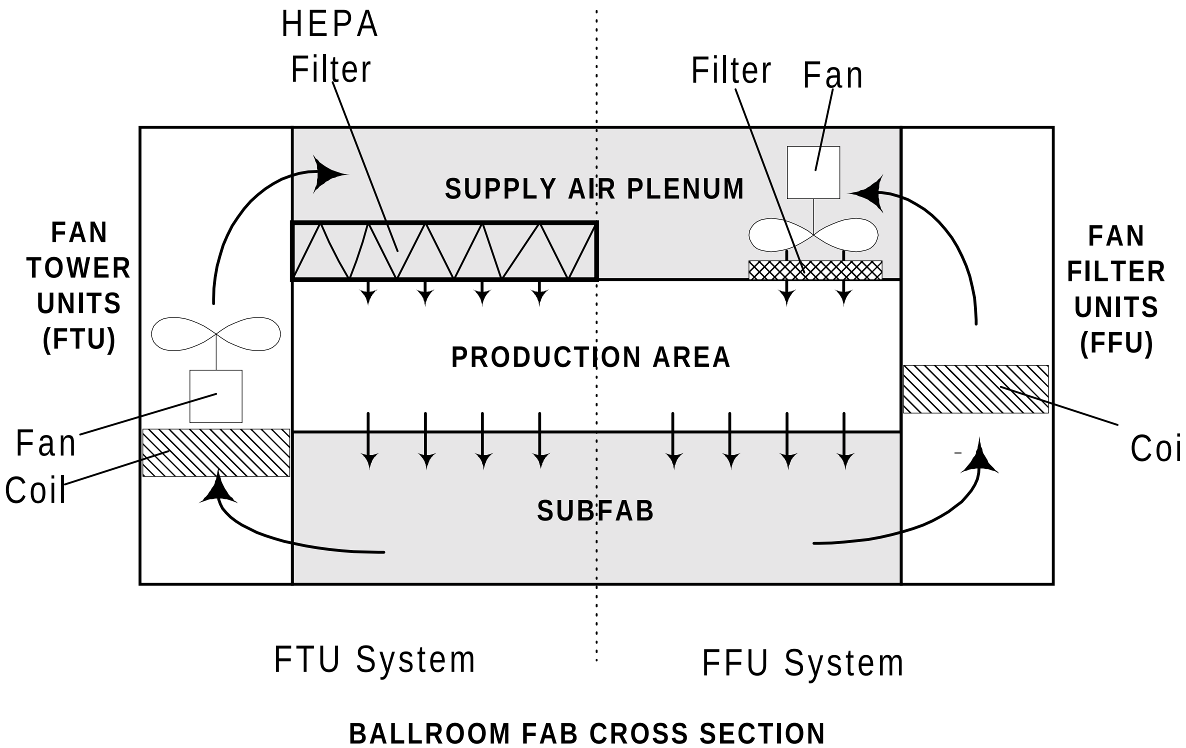


Figure 3-13
Schematic of a Fan Tower Unit (FTU) and a Fan Filter Unit (FFU)

Fan filter units (FFUs) have the same general flow path as the FTU systems. FFU fans are typically very small horsepower variable drive or damper-controlled units that are located in the ceiling along with the HEPA filter. The advantage of the FFU system is that it provides better control of the air flow through the cleanroom, which, in turn, can provide better temperature control and removal of particulates generated within the fab.

The third type of recirculation system is a modification of the fan tower system described above that is characterized as a minienvironment. Minienvironments provide additional filtration at the tool level, protecting the wafers from the fab cleanroom environment as they are moved from tool to tool. One of the advantages of a minienvironment design is that fab cleanroom classification requirements can be reduced for the same manufacturing geometry. Reducing the cleanroom classification can result in lower energy use in the recirculating air system because of reduced air flow and filtration requirements.[11] General data about the recirculating air systems at the participating fabs are presented in Table 3-5.

[11] Some additional energy would be used at the minienvironments at each tool; a minienvironment fab would probably still be designed with an FFU, though the demand on the FFU system would be lower than otherwise.

Table 3-5
Recirculating Air System Data

Fab Number	General Data								
	Air Velocity[1]		Fab Temperature Setpoint		HEPA Coverage Area	Fab Humidity	Fab Pressurization		Makeup Air Volume as a Percentage of Recirculating Air Volume[2]
	ft/min	m/min	F	C	(within cleanroom) % total	%	(in. H2O)	Pascals	%
1	89	27			70%	40±2 45±5	0.18	45	6.5%
2	89	27	72	22	20%	43±3	0.18	45	2.0%
3	69	21	73	23	80%	45±2	0.12	30	11.2%
4	59	18	73	23	52%	45±3	0.17	43	35333.8%
5	98	30	73	23	80%	45±5	0.04	10	7.8%
6	63	19	72±2	22±1.3	73%	42±2	0.10	25	5.9%
7	69	21	72±5	22±.3	69%	43±3	0.05	13	25.5%
8	49	15	72±1	22±1	25%	45±5	0.10	25	27.3%
9	70	21	67	19	70%	47	0.04	10	10.7%
10	70	21	68	20	70%	42	0.00	0	8.3%
11	90	27	67 TO 70±2	19±.6 to 21±1.2	30%-100%	42.5±5	0.02	5	21.7%
12	30	9	68±2	20±1	100%	39±4	0.05	11	31.1%
13	83	25	70	21	65%	45±2	0.08	20	5.3%
14	80	24	70±1	21± .7	100%	45± 2	0.01	2	14.8%

[1] 6 inches below HEPA filters.

[2] Calculated as the average flow (cfm) of the makeup air divided by the sum of the average flows in FTUs and FFUs. Value for fab 4 is outside reasonable bounds, but is based on data submitted by the fab.

Note: Blank cells indicate data not submitted. Data appears as submitted by respondent.

Table 3-5 (continued)
Recirculating Air System Data

Fab Number	Air Handling Unit Data												
	Fan Tower Units				**Fan Filter Units**				**Discharge Temperature Setpoint**		**Average Sensible Cooling Load**		**Sensible Cooling Load**
	Units	average measured electric load (all units) kW	Average Unit Flow		Units	average measured electric load (all units) kW	Average Unit Flow		°F	°C	(tons of refrig.)	kW	%
			CFM	CMH			CFM	CMH					
1	69	1,565	3,018,113	5,125,057	370	105	39,574	67,201	71	22	1,090	3,832	
2	58	650	2,787,146	4,732,852	1,180	473			64	18	4,454	15,660	100
3	33	873	1,990,647	3,380,317	1,273	199	462,699	785,709	73	23			100
4					4,200	581	487	827	72	22	856	3,010	100
5	74	1,962	2,944,500	5,000,055					73	23	1,305	4,588	100
6	40	1,927	2,691,080	4,569,723					72	22	548	1,927	100
7	21	580	653,679	1,110,012	19				72	22	203	713	100
8	10	346	882,437	1,498,467					69	21	0	0	100
9	22	608	995,000	1,689,610	110	351	640,000	1,086,784	67	20	312	1,097	100
10	25	820	2,000,000	3,396,200					68	20			100
11	96	3,000	4,800,000	8,150,880					67	19			
12	142	2,090	2,272,000	3,858,083	115	32	20,700	35,151	55-67	12.8-19.5	1,255	4,413	100
13	61	950	1,766,700	3,000,033	N.A.				70±2	21±1	711	2,500	100
14			1,717,388	2,916,297		1,600	18,000	30,566	70	21	600	2,110	

Note: Blank cells and zeros indicate data not submitted. Data appears as submitted by respondent.

Results

Recirculating air flow is a function of the design of the fab and local operation of the system. Recirculating air system efficiency for the participating fabs can be measured as cfm per kW (shown in Figure 3-14).

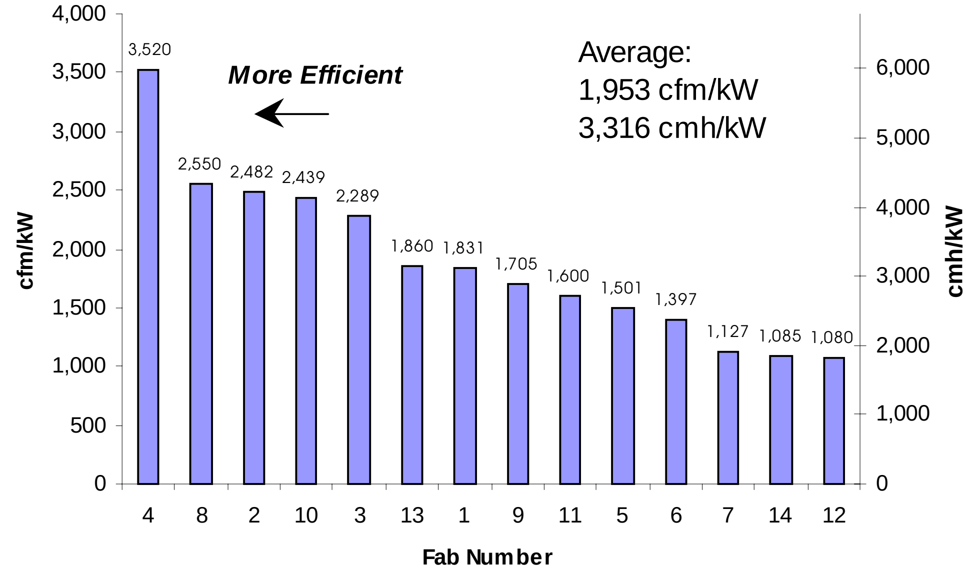


Figure 3-14
Recirculation Unit Fan Efficiencies

The average efficiency for the recirculating systems was 1,953 cfm/kW (3,316 cmh/kW). Efficiency levels ranged from a low of 1,080 cfm/kW (1,834 cmh/kW) at fab 12 to a high of 3,520 cfm/kW (5,977 cmh/kW) at fab 4.

The data from fab 4 appeared to be in error, although it was the only fab surveyed that reported FFU data without reporting any FTU data. The next most efficient fab (fab 8) reported one of the lowest HEPA velocities (49 feet per minute, 15 meters per minute) among the fabs studied. The system uses FTUs in a 3-year old fab ballroom/minienvironment type facility. In contrast, the second most efficient fab (fab 2) reported one of the highest HEPA velocities (89 feet per minute, 27 meters per minute), but the HEPA coverage area within the cleanroom was only 20%—the lowest coverage area of all the fabs studied. Fab 2 is a 4-year old minienvironment facility. The third most efficient fab was fab 10, a 3-year old ballroom style fab with oversized FTUs and variable pitch vane axial fans. Fab 12, the lowest efficiency system, was in a 15 year old facility with an FTU system. Data submitted shows that this fab uses the lowest HEPA velocity in the study (30 feet per minute, 9 meters per minute) combined with 100% HEPA coverage, which should contribute to an efficient system. It is unclear why this system's performance is so low.

The second critical measurement for the recirculating system is the amount of energy required to run the fans. The normalized energy requirement of the recirculating air systems is shown in Figure 3-15. The average value for this indicator is 0.046 kWh per unit of production.

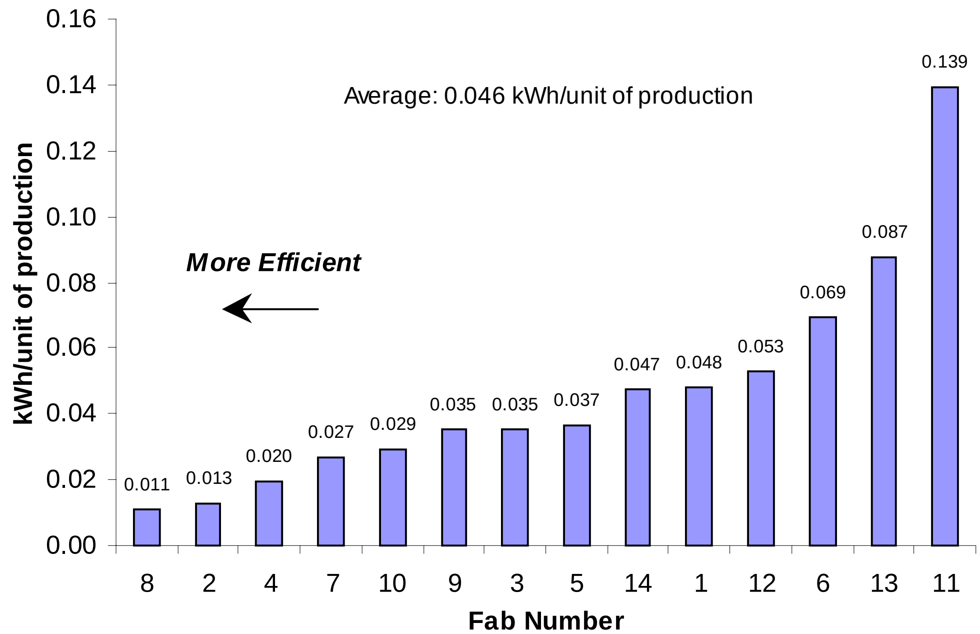


Figure 3-15
Recirculating Systems Energy Usage Normalized by Units of Production

Fabs 8, 2, and 4 consume the least amount of energy for recirculating air within the cleanroom (these fabs were also among the top three performers in the calculation of recirculating unit fan efficiencies, above). Fab 8 is an FTU system with a low reported HEPA velocity and a low (25%) reported HEPA coverage area; this fab has minienvironments. Fab 4 is an FFU system that reported a medium HEPA velocity (59 feet per minute, 18 meters per minute) and a medium (52%) HEPA coverage area. Fab 2 is also an FFU system; it reported a medium HEPA velocity (69 feet per minute, 21 meters per minute) and a low (20%) HEPA coverage area. Fab 2 reported the highest production level of any fab in the study.

Fab 11 uses the largest amount of energy per unit of production for recirculating air. It is an FFU system in an 11-year old facility; the fab reported the highest average measured electric load (kW) and the highest average unit flow (cfm or cmh) of all the fabs studied.

Recirculating Air Systems Top Performers—Detailed System Information and Best Practices

Fab 8

- **System Description**

The measured air velocity (6 inches (152 mm) below HEPA filters) in the recirculating air system of fab 8 was 49 feet (15 meters) per minute. The fab temperature setpoint is 72°F (22°C) ± 1°F. HEPA coverage area within the cleanroom is 25% of the total cleanroom area. Fab humidity is kept at 45%, plus or minus 5%, and pressurization is kept at 25 Pascals (0.10 in. H_2O).

The recirculating air system operates at the design flow rate of 100 113 cfm (170,000 cmh) per FTU with a total of ten units running. High efficiency motors are used, with the fan design efficiency rating from the manufacturer at 76.7%. The actual static pressure in the recirculating air units is 300 Pascals (1.21 in. H_2O) compared to the design static pressure of 350 Pascals (1.41 in. H_2O).

The fab has 12 recirculating fan systems, but only ten are operated and the other two are used for backup. The fans are not equipped with any type of volume control.

The system uses ultra low particulate air (ULPA) filters and changes them out based on monthly particle counts, in addition to real-time monitoring. If areas show a burst of high particles, further filter scanning is done. The pressure drop across the filters is 100 Pascals (0.40 in. H_2O). The actual filter velocity is 0.28 meters per second (0.91 feet per second) compared to their design velocity of 0.25 meters per second (0.82 feet per second). The ULPAs are 4 years old.

- **Data Collection Methodology**

All air flow measurements at fab 8 were accomplished with a calibrated vane type anemometer. Readings obtained correlated with cleanroom commissioning data. The kW was measured using a power monitor unit.

- **Conclusions**

Fab 8 excels in low recirculation volume per unit of production and reported the lowest volume among all the sites surveyed. The low volume may be a factor of the class 100 rating accompanied by minienvironment equipment. The fab is working with 0.35 µm technology.

Recirculating system efficiency was higher than the average fab surveyed but was not exceptional. The system efficiency does not appear as high as expected for a system with only 300 Pascals (1.21 in. H_2O) pressure differential across the fan. The measured power is 34.6 kW per fan. The rated motor power is 37.3 kW. The actual operation is 93% of design.

Facility engineering staff at fab 8 believe that their fab performed well in this area because it has a class 100 cleanroom design with an air change of 70 times per hour. The cleanroom has a lower air flow rate compared to higher cleanliness cleanrooms. This leads to lower operating electrical consumption. Minienvironments are incorporated in process tools to achieve class 1 cleanliness.

Fab 4

- **System Description**

The measured air velocity (6 inches (152 mm) below HEPA filters) in the recirculating air system of fab 4 was 59 feet (18 meters) per minute. The fab temperature setpoint is 73°F (23°C). HEPA coverage area within the cleanroom is 52% of the total cleanroom area. Fab humidity is kept at 45% ± 3%, and pressurization is kept at 43 Pascals (0.17 in. H_2O).

The design flow rate of the system is 7,140,516 cfm (4,205,050 cmh). This value is 1.3 times the actual flow rate of 2,044,567 cfm (3,471,840 cmh), because facility staff has set the safety factor as 0.3. The static pressure in the recirculating air units is 50 Pascals (0.20 in. H_2O) compared to the design static pressure of 70 Pascals (0.28 in. H_2O). The system uses ultra low particulate air (ULPA) filters and pre-filters. These filters are replaced based on pressure drop, particle status, and efficiency. The filter velocity varies from 0.37 to 0.45 meters per second (1.21 to 1.48 feet per second) compared to the design velocity of 0.58 meters per second (1.90 feet per second). High efficiency motors are used.

- **Data Collection Methodology**

The data were collected with portable spot and trend meters. Recirculating air flow volume was measured in the return air duct by the project contractor. Metering equipment is calibrated on an annual basis.

- **Conclusions**

Facility engineering staff at fab 4 believe that the fab performed well in this area because it is designed more efficiently, has better operations management, and uses more efficient motors, filters, and other accessories. The staff believe that the following contribute to power consumption savings:

- Best layout design
- Best air velocity adjustment for FFU
- Cleaning pre-filters at regular intervals

The recirculating fan system at this site excels in efficiency. The FFU system has the highest efficiency of any of the sites in the survey and is twice as high as the next best fab. The static pressure across the fan systems is extremely low and the differential pressure across the fan and ULPAs is 80–83 Pascals (0.32–0.33 in. H_2O). The low pressure drop indicates that the pressure measurement may have been taken between the suction side of the fan and the discharge side of the ULPAs, and therefore may actually reflect the pressure drop in the return air plenum rather than the pressure drop across the fans or across the ULPAs.

The recirculated air quantity is one of the highest in the survey even though the velocity at the ceiling is only 59 ft/min. (18 m/min.). The flow data submitted is inconsistent with the calculated flow. Calculating the air flow based upon cleanroom area, ULPA coverage area, and flow velocity at the ceiling below the ULPAs yielded a calculated air flow value of approximately 33% of the supplied measured flow rate and 25% of the design flow rate.

Fab 2

- **System Description**

The measured air velocity (6 inches (152 mm) below HEPA filters) in the recirculating air system of fab 2 was 89 feet per minute (27 meters per minute). The fab temperature setpoint is 72°F (22°C). HEPA coverage area within the cleanroom is 16% of the total cleanroom area. Fab humidity is kept at 43%, ± 3%, and pressurization is kept at 45 Pascals (0.18 in. H_2O).

The design flow rate of the system is 1,548,140 cfm (2,628,897 cmh) compared to the actual flow rate of 1,376,120 cfm (2,336,789 cmh). The design static pressure in the recirculating air units is 250 Pascals (1.01 in. H_2O). The actual design static pressure is 200 Pascals (0.80 in. H_2O).

The system usesULPA filters, which are replaced every 5 years. The filter loading is checked every year. The pressure drop across the ULPAs is 125 Pascals (0.50 in. H_2O). The filter design velocity is 0.46 meters per second (1.50 feet per second) compared to the actual filter velocity of 0.41 meters per second (1.33 feet per second). Variable speed drives control the fan volume, and high efficiency motors are used.

- **Data Collection Methodology**

The metering for both the electrical and flow measurements was performed with high quality instrumentation. Two units in one of the two fabs at this site and one unit in the other fab were spot-metered and the results were multiplied by the number of similar units and hours per year of operation.

- **Conclusions**

Fab 2's recirculating air system uses an extremely low pressure drop across the fans and filters to keep the system efficiency high. The recirculating rate is the factor that provides the greatest energy reduction in system operation. The velocity below the filters is a fairly typical to high 27 meters (89 feet) per minute but the filter coverage is only 16%, which results in an extremely low number of air changes per hour (see the chart, Return Air Handler Air Changes Per Hour, in Appendix G). The combination of these factors move this site to one of the lowest usage rates among fabs for the recirculating systems. The fab also uses minienvironments, which may be a major factor allowing the fab to operate at its low recirculating rate. Average air velocity within the ballroom is 0.1 meters (0.33 feet) per second and the systems are operating at 88% of design flow rate.

The low energy use of the recirculating system directly translates into lower heating load within the fab that must be handled by the central chiller plant.

The air flow, static pressure, and energy use submitted for this survey do not appear to be consistent. Although the site survey included two fabs equal in size and production output, the recirculating air flow reported appears to have included only one of the fabs. Therefore, actual air flow may be higher than what was reported. This observation also appears to be consistent with the expected air flow calculated for the fab size and average air velocity. However, even with the uncertainty in the data, this fab would still rank among the top performers even if its air flow data were doubled. The electrical data submitted appears to be large enough for both fabs.

Exhaust Air System

Description

There are five different types of exhaust systems:

- General
- Scrubbed
- Solvent
- Acid
- Ammonia

Every fab has at least one type of exhaust system; some fabs have several to handle different types of exhaust. General data about the fabs' exhaust systems are shown in Table 3-6.

Table 3-6
Exhaust Air Systems Data

Fab Number	General Exhaust System					Scrubbed Exhaust System					Solvent Exhaust System				
	Variable Flow	# of Fan units	Average measured electric load (all operating units) kW	Average Flow CFM	Average Flow CMH	Variable Flow	# of Fan units	Average measured electric load (all operating units) kW	Average Flow CFM	Average Flow CMH	Variable Flow	# of Fan units	Average measured electric load (all operating units) kW	Average Flow CFM	Average Flow CMH
1	No	16	330	167,837	285,003	No	11	290	146,636	249,003	No	5	40	21,200	41,998
2	Yes	32	248	414,831	704,425	Yes	19	320	125,085	212,406	Yes	4	58	25,016	42,480
3	Yes	8	129	106,991	181,682						Yes	4	38	25,016	42,480
4	Yes	3	90	47,419	80,522						Yes	3	54	17,331	29,430
5						Yes	3	295	104,824	178,002	Yes	2	120	13,339	22,650
6											Yes	1	173	16,500	28,019
7	Yes , 1 fan	2	75	33,921	57,601						Yes, 1 fan	2	16	14,840	25,200
8	Yes	4	115	101,944	173,111	Yes	5	155	155,081	263,343	Yes	3	36	45,808	77,787
9	Yes	9	160	135,093	229,401										
10	Yes		101	43,210	73,375	Yes		57	17,880	30,362	Yes		41	17,880	30,362
11	No	120	300	186,200	316,186	Yes	7	720	244,000	101,886	No	4	100	19,800	33,622
12	Yes	12	508	460,000	781,126	No	3	208	60,000	101,886	No	6	110	38,000	64,528
13	No	4	53.8	44,756	76,001	No	4	49.8	41,223	70,000					
14	No	3	32	17,500	29,717	No	6	390	135,000	229,244	No	5	54	27,400	46,528

Note: Blank cells and zeros indicate no data submitted. Data appears as reported by respondent.

Table 3-6 (continued)
Exhaust Air Systems Data

Fab Number	Acid Exhaust System					Ammonia Exhaust System				
	Variable Flow	# of Fan units	Average measured electric load (all operating units) kW	Average Flow		Variable Flow	# of Fan units	Average measured electric load (all operating units) kW	Average Flow	
				CFM	CMH				CFM	CMH
1	No	6	255	122,491	208,002					
2										
3	Yes	8	144	102,327	173,762	No	2	10	5,757	9,775
4	Yes	4	161	106,881	181,494	Yes	3	34	8,207	13,937
5	Yes	4	363	107,415	182,402					
6	Yes	8	237	120,000	203,772	Yes	2	84	15,000	25,472
7	Yes, 2 fans	4	103	63,813	108,361	Yes, 2 fans	3	28	17,384	29,520
8										
9										
10	Yes		6	67,050	113,858	Yes			2,980	5,060
11										
12	Yes	1	37	46,000	78,113					
13										
14										

Note: Blank cells and zeros indicate no data submitted. Data appears as submitted by respondent.

Results

Of the 14 fabs surveyed, ten have a general exhaust system, nine have a scrubbed exhaust system, twelve have a solvent exhaust system, eight have an acid exhaust system, and five have an ammonia exhaust system. The absence of a type of exhaust system in any fab typically means that data for the system is combined with data for another type of system.

The exhaust air energy use includes only the energy needed to operate the exhaust fan systems. The exhaust analysis in this report represents the combined exhaust of all systems in the fabs. Efficiency is represented by the total exhaust air flow divided by the total electricity usage in kW for all operating exhaust fan motors (Figure 3-16).

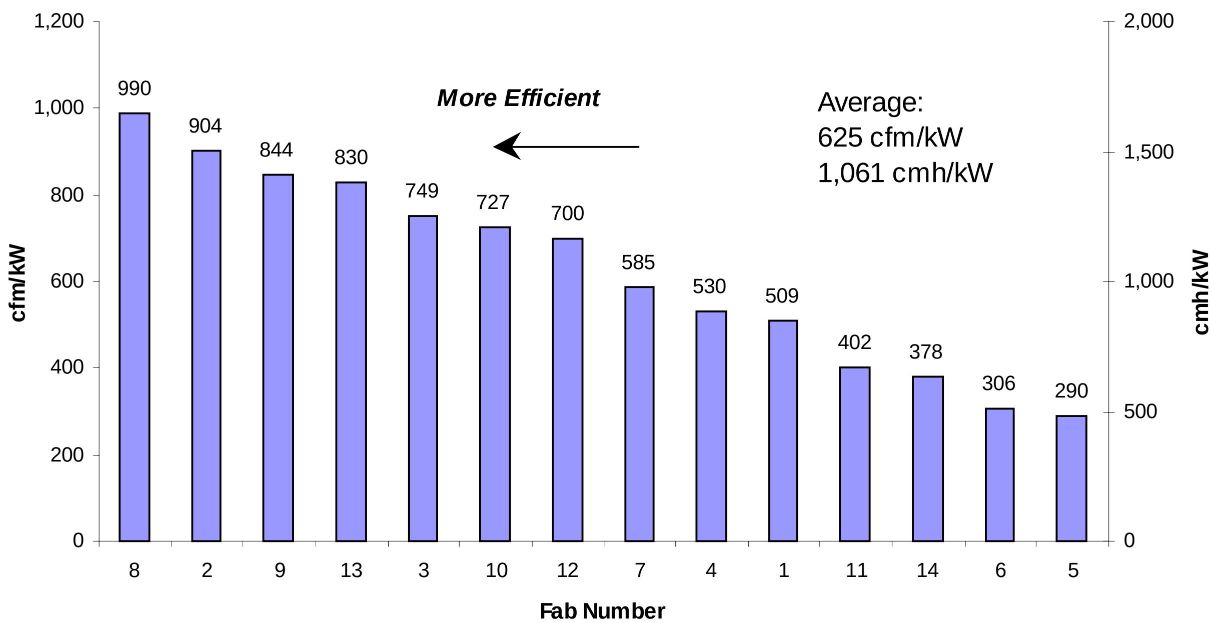


Figure 3-16
Exhaust Fan Efficiencies

Airflow measurements typically have an accuracy of plus or minus 5% of measured air flow. Differences in flow of less than 5% should not be considered significant. The efficiency of the exhaust systems is related to duct sizing, fan efficiencies, and balancing. The most efficient exhaust fan systems are at fab 8 with 990 cfm/kW (1,681 cmh/kW), fab 2 with 904 cfm/kW (1,535 cmh/kW), and fab 9 with 844 cfm/kW (1,433 cmh/kW). The least efficient systems are at fabs 1 and 5 with 287 and 290 cfm/kW (487 and 492 cmh/kW), respectively. The average value for exhaust system efficiency is 609 cfm/kW (1,034 cmh/kW).

Figure 3-17 illustrates the annual exhaust fan energy required per unit of production for each fab. The average value for the exhaust fan energy is 0.014 kWh per unit of production. Fab 9, at 0.006 kWh per unit of production, requires the least exhaust fan energy. Fab 11 recorded the greatest amount of exhaust fan energy per unit of production by a factor of about 4 over the average value. This large deviation indicates that the fan energy data for fab 11 may be suspect.

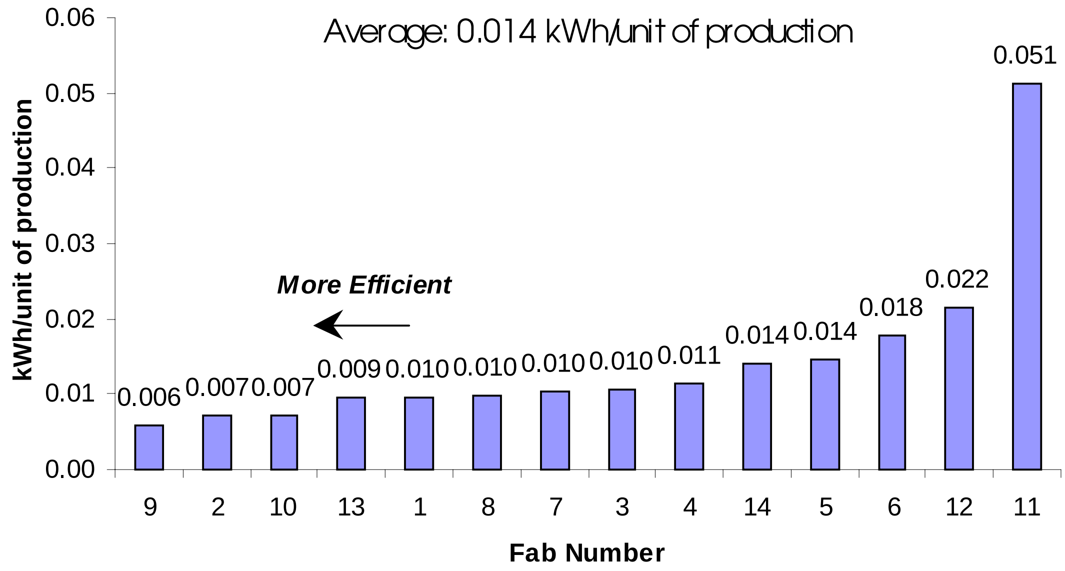


Figure 3-17
Exhaust Fan System Energy Usage Normalized by Units of Production

The fabs with higher exhaust fan energy use per unit of production indicate that either the production rate or the fan efficiency is low, possibly because of the age of the system or the number of retrofits that have been undertaken.

Exhaust Systems Top Performers—Detailed System Information and Best Practices

Fab 9

In reviewing the exhaust data, the fab 9 engineering staff concluded that inaccuracies in the data resulted in their fab's favorable performance. They have two distinct exhaust systems, but the data accounted for only one of them. The staff does not believe their system can be operating efficiently enough to be recognized as a top performing facility.

The data for this site were collected during the original pilot study, which was an aggregate for the facility that included both fully and partially operational fabs that had not been fully populated with tools. Inclusion of this site in the survey, without a completely new survey, required allocation of loads within the multiple fabs based upon best estimates where supporting data were not available. Since the initial survey, the fab operation and tool population have changed significantly and further verification of the initial data (including metered and production data) is not available.

Fab 2

- **System Description**

The general exhaust air system of fab 2 uses 32 variable flow fan units with an average measured electric load of 248 kW and an average flow rate of 414,831 cfm (704,425 cmh). The fab also has a scrubbed exhaust system and a solvent exhaust system. The scrubbed exhaust system uses 19 variable flow fan units with an average measured electrical load of 320 kW and an average flow rate of 125,085 cfm (212,406 cmh). The solvent exhaust system uses five fan units with an average measured electrical load of 40 kW and an average flow rate of 25,016 cfm (42,480 cmh).

The manufacturer's exhaust fan design efficiency rating is 90%. The exhaust air system operates at its design static pressure of 1,493 Pascals (6 in. H_2O). The actual flow in the exhaust air system is 189,400 cfm (321,620 cmh) compared to a design flow of 195,000 cfm (331,130 cmh). Burn boxes, scrubbers, air washers, controlled decomposition/oxidation, and volatile organic compound (VOC) zeolite concentrators are used to control pollution. The exhaust system is periodically rebalanced when new tools are installed.

Fab 2 has upgraded its exhaust air system by installing a local scrubber to reduce the product of crystallization in the duct when alkaline air is separated from acidic air.

- **Data Collection Methodology**

The individual exhaust fan systems in each of the fabs was trend-metered for 24 hours to determine the average energy consumption. More detailed information about the data collection methodology at this site was unavailable. The magnitude of the design and actual data submitted in the final request appear to indicate that the air flow measurements may apply to only one of the two fabs included at this site. The overall exhaust flow data for the individual systems originally submitted were used in exhaust air flow evaluations.

- **Conclusions**

Selection of this site for best practice evaluation was based upon the energy use per unit of production. Data on energy use appear to have been carefully and accurately collected. The major factors that seem responsible for the low energy use are high fan efficiency combined with an average exhaust rate per unit of production.

The original air flow data submitted by this fab appear to more closely match anticipated exhaust flow than the data resubmitted in subsequent data revisions. These newer data are presented above. Exhaust flow identified higher than 195,000 cfm (331,130 cmh) may account for only one of the two fabs at this site; it is too low to match the exhaust system kW, static pressure, and fan efficiency data. The calculated air flow of the system based upon overall energy use, fan static, and fan efficiency would be 860,000 cfm (1,460,366 cmh), which is 96% of the makeup air volume. The originally submitted data indicate exhaust air flow of 565,000 cfm (959,427 cmh).

The discrepancy may identify a weakness in the simplified data collection procedure used in this survey. The exhaust systems in fabs typically contain multiple fans, each of which may have a different static pressure. The simplified data collection form, which allows only a single static pressure to be submitted for the exhaust systems, may be a potential source of error.

Fab 10

- **System Description**

The general exhaust air system of fab 10 uses variable flow fan units with an average measured electric load of 101 kW and an average flow rate of 43,210 cfm (73,375 cmh). The fab also has separate systems for scrubbed exhaust, a solvent exhaust, acid exhaust, and ammonia exhaust. The scrubbed exhaust system uses variable flow fan units with an average measured electrical load of 57 kW and an average flow rate of 17,880 cfm (30,362 cmh). The solvent exhaust system uses variable flow fan units with an average measured electrical load of 41 kW and an average flow rate of 17,880 cfm (30,362 cmh). The acid exhaust system uses variable flow fan units with an average measured electrical load of 6 kW and an average flow rate of 67,050 cfm (113,858 cmh). The ammonia exhaust system uses variable flow fan units with an average flow rate of 2,980 cfm (5,060 cmh).

- **Data Collection Methodology**

The data for this fab was not originally metered for this survey and was adapted from a previous survey. The original survey metered the energy use for the fab, but only one-half of the fab was in production. As a result, many of the systems were oversized for the actual load at the time, but would not maintain the same efficiency level when the entire fab was populated with tool and placed in operation.

- **Conclusions**

The exhaust air system’s high performance at fab 10 is the result of a combination of high efficiency systems and additional efficiency because of partial operation of the fab. Actual energy use was allocated between the operating and the non-operating portions of the fab, but the impacts of a dramatic increase in total load on the support systems as fab production increased was not included in the measured values.

Fab 8

Engineering staff at fab 8 cited the fab’s use of variable speed drives for all general exhaust, scrubber exhaust, and solvent exhaust fans as responsible for its favorable performance. However, the staff have confirmed that the measured exhaust fan electrical consumption submitted in the energy audit report is incorrect. The power meter that was used is not suitable to measure the variable speed drive output, giving a much lower electrical consumption.

The electrical data were remetered for power consumption, and new exhaust volume data were submitted that increase both the power consumption and exhaust flow of the site. Since these new measurements increase energy use of the site per unit of production, it is no longer considered one of the top performing sites.

Nitrogen Plant

Description

All fabs use nitrogen for operating their tools; some use it in place of compressed dry air for facility control or other systems. Although all plants appear to use nitrogen, most do not own the nitrogen generators. Nitrogen is typically purchased from another company and generated by a plant that may or may not be on the facility premises. If the plant is sited at the fab, the utility cost for operating the plant is generally known. If the plant is located offsite, utility consumption data may not be available. General data about the nitrogen systems in the participating fabs are shown in Table 3-7.

Table 3-7
Nitrogen Systems Data

Fab Number	Average Measured Electric Load	Average Measured Flow Rate	
	kW	CFM	CMH
1	860	1,132	1,922
2	440	471	800
3	719	1,847	3,136
4		51,732	87,846
5	1,296	1,440	2,445
6		1,450	2,462
7	323	1,065	1,808
8	841	1,400	2,377
9	800	1,250	2,123
10	1,850		
11	750	28,000	47,547
12	1,448	3,000	5,094
13	270	530	899
14	2,274	1,598	2,714

Note: Blank cells indicate data was not submitted.
Data appears as submitted by respondent.

Results

Twelve of the 14 fabs submitted the electrical demand of the nitrogen plant. Eleven submitted both the consumption and the nitrogen flow rate. Fab 11 submitted data on both the measured electrical load and flow rate, but the flow rate data were outside reasonable bounds and thus not used in further calculations. Plant efficiency was measured in standard cubic feet per minute (scfm) or standard cubic meters per hour (scmh) per kW. Efficiencies for the fabs, as shown in Figure 3-18, have an average value of 1.73 scfm/kW (2.94 scmh/kW). The most efficient fabs are fabs 7, 3, and 12, with efficiencies of 3.30, 2.57, and 2.07 scfm/kW (5.60, 4.36, and 3.52 scmh/kW), respectively.

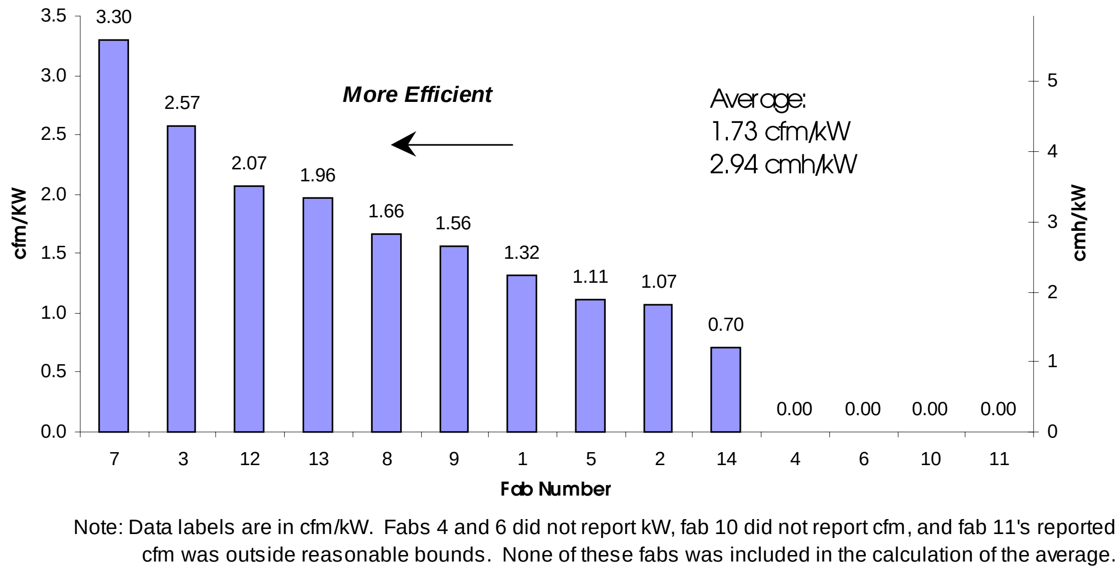


Figure 3-18
Nitrogen Plant Efficiencies

Figure 3-19 illustrates the annual energy required to produce nitrogen per unit of production for each fab. The average value for this metric is 0.031 kWh per unit of production. This chart shows considerable diversity among the fabs. This diversity may be attributable to the allocation of nitrogen production between more than one facility. The most efficient fabs in terms of nitrogen system energy use per unit of production are fabs 2, 7, and 3. Fabs 4 and 6 likely reported zero energy for nitrogen production because they purchase bulk gas in tanker trucks.

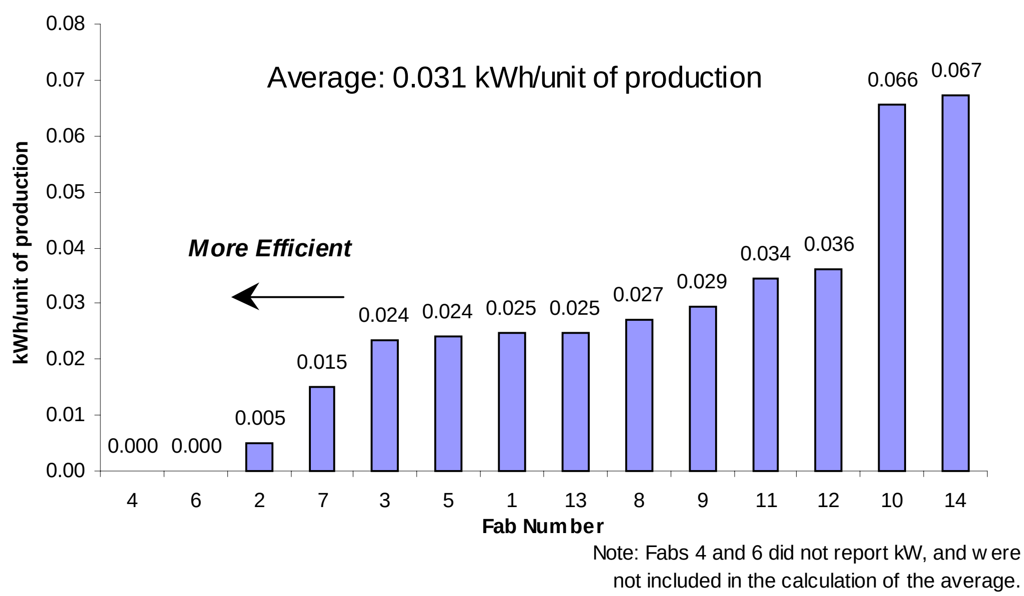


Figure 3-19
Nitrogen System Energy Usage Normalized by Unit of Production

Nitrogen Systems Top Performers—Detailed System Information and Best Practices

Fab 2

- **System Description**

Fab 2's nitrogen system has an average measured electrical load of 440 kW and an average measured flow rate of 471 cfm (800 cmh). The nitrogen system is not metered separately from the remaining facility. The system operates at its full design capacity of 800 scfm (1,358 scmh). A water chiller of 48°F (9°C) is the cooling source for the nitrogen plant. Approximately 5% of the nitrogen system capacity is used for other fab processes. The purity specification of the nitrogen manufactured is 100 ppb O_2. The nitrogen plant was manufactured by BOC.

- **Data Collection Methodology**

The data metered included the total electrical input to the nitrogen plant located at the fab; the flow rate of the nitrogen was metered with inline flow metering devices. The last calibration date of the meters is not known.

- **Conclusions**

The metering did not include supplemental nitrogen provided by a nitrogen plant at a remote location, but it did include all the nitrogen flow from the plant. This factor may have introduced significant error in the measurement of this utility.

Fab 7

- **System Description**

Fab 7's nitrogen system has an average measured electrical load of 323 kW and an average measured flow rate of 1,065 cfm (1,808 cmh). The nitrogen system is operating at the full design capacity of 105,944 ft^3 (3,000 cubic meters) of nitrogen. The cooling source for the nitrogen plant is a 91°F (33°C) water chiller. The nitrogen system is used only for providing nitrogen to processes. The purity specification of the nitrogen is 10 ppb O_2. The nitrogen plant was manufactured by Air Liquide.

The nitrogen system produces liquid nitrogen in addition to nitrogen in gas form. The system can produce 100 m^3/hour of liquid nitrogen, which can be stored for emergency or peak use. The plant is sized very close to the average plant load, and peak load periods may require supplemental nitrogen. One tanker truckoad of supplemental nitrogen (max. 13000 m^3) is used each month for each of the two fabs at this site. The discharge pressure is 7.5 bar at one fab and 8.9 bar at the other fab.

- **Data Collection Methodology**

The energy required to provide cooling to the nitrogen plant was not included in the nitrogen plant data submitted. This would increase the kWh per unit of production above the values calculated in this study.

- **Conclusions**

Fab 7 facilities engineers believe that this fab performed well in the nitrogen area because the compressor size and the EPROM for the nitrogen purifier were upgraded.

The facility implemented a plant-wide utilities reduction effort in March 1997. They reduced consumption in June 1997, mainly through reduction in equipment purge from 2,600 cmh (1,531 cfm) to 1,650 cmh (972 cfm). This came about mainly from sealing purge enclosures and leak points and reducing pressure specifications.

The facility also uses small amounts of supplemental nitrogen for peak loads. The amount of supplemental nitrogen does not appear to be significant.

Fab 3

- **System Description**

Fab 3's nitrogen system has an average measured electrical load of 719 kW and an average measured flow rate of 1,847 cfm (3,136 cmh). The system has an operating capacity of 2,500 scfm (4,245 scmh) compared to the design capacity of 2,900 scfm (4,924 scmh). An expander (32°C) is the cooling source for the nitrogen plant. The purity specification of the nitrogen manufactured is 500 ppb O_2. The nitrogen plant, manufactured by Air Products, is used only to supply nitrogen to processes. The plant uses liquid nitrogen recovery.

An earlier study of the fab concluded that a total of 17,247 kWh per day was consumed by the nitrogen plant, of which 97.7% was consumed by air compressors and only 2.3% by pumps. The study also concluded that the nitrogen plant represents 9% of the total facility load at this fab.

- **Data Collection Methodology**

The data metered included the total electrical input to the nitrogen plant located at the fab. The flow rate of the nitrogen was metered with inline flow metering devices. The last calibration date of the meters is not known.

- **Conclusions**

Facility engineers at fab 3 believe that its liquid nitrogen backup system sets this fab apart from others. If the air compressor alone cannot supply the required quantity of nitrogen, the backup system will automatically supply nitrogen to the end user. In addition, the plant has undergone some upgrades in the past several years. The system was upgraded from a 10 RA surface finish high purity nitrogen to a 12 RA surface finish high purity nitrogen system in 1996; another 10 high purity nitrogen system was installed in 1997. Increasing the nitrogen system capacity is an efficiency improvement because it reduces or eliminates the need to purchase supplemental nitrogen. This improvement gave the fab sufficient bulk gas. The gas supply has not been interrupted, and the quality of the supplied gas has been kept in good condition.

The nitrogen system has the capacity to use liquid nitrogen to supplement the nitrogen created by the plant. The facility staff's comments indicate this capability but do not specify whether and when it is used or how much is used by month or year. The use of supplemental nitrogen would give the fab the appearance of lower than actual nitrogen consumption. The efficiency of the nitrogen plant in this facility was lower than the average plant in the survey, but the fab's actual use of nitrogen is one of the lowest in the survey. The nitrogen purity also appears to be lower than the purity specification of some of the other fabs.

Fab 5

- **System Description**

Fab 5's nitrogen system has an average measured electrical load of 1,296 kW and an average measured flow rate of 1,440 cfm (2,445 cmh). The fab's nitrogen system is a co-production system, in which compressed dry air and nitrogen are produced together from one main compressor. The main compressor supports 5 fabs, including the one included in this study. The flow rate was allocated to this particular fab based on utility distribution criteria. From the main compressor, the nitrogen production rate accounts for about 50% of the total suction rate. There are four main compressors, and each compressor supports five production and two research fabs.

The design capacity of the nitrogen system is 9,717 cfm (16,500 cmh), including compressed dry air. The cooling source for the nitrogen plant is a water chiller at 26°C. Less than 1% of the nitrogen system capacity is used for purposes other than providing nitrogen to processes. The nitrogen plant was manufactured by the Korean company, Dae Sung.

- **Data Collection Methodology**

Both compressed dry air and nitrogen are supplied from the same compressor system and could not be independently electrically metered. The overall compressor electrical load was measured and the electrical use for compressed dry air and nitrogen was determined based upon the gas flow rate for each service out of the compressor. In addition, although the compressed dry air was measured at the fab submitted, the nitrogen system was not equipped with an existing metering system and was measured at an identical fab at the same location with the same production rate. The flow meters are hot wire anemometers installed when the fab was built in 1994. They have not been recalibrated since installation.

- **Conclusions**

This fab's performance is due to a combination of lower than average nitrogen/compressed dry air efficiency with significantly lower than average compressed dry air and nitrogen use. The low efficiency is probably due to the partially loaded operation of the compressor system (it runs at approximately 50% of its design capacity). Nitrogen is used for typical purposes such as vacuum pumps, wafer drying, and boat washing. The fab has not implemented any program to reduce nitrogen consumption or compressed dry air use.

Compressed Dry Air Plant

Description

Compressed dry air is required for operating the facility control systems within a fab or for supplying air to burn boxes that are used in exhaust stream treatment. Supply pressures are usually in the 110–120 psi (758-827 kPa) range. A compressed dry air plant may be a standalone system, using additional compressors or the nitrogen system for backup. Some facilities produce compressed dry air in conjunction with nitrogen making it impossible to separate the energy requirement for compressing the air alone.

Fabs typically use large screw or centrifugal compressors for their durability and large volume capacity. Screw compressors are generally less expensive than centrifugal compressors, but centrifugal compressors tend to have a slightly higher efficiency and better unloaded operation performance. Screw compressors may perform better in cold climates. Centrifugal compressors generally have constant electrical loads despite changing weather conditions.

Operating factors can also affect the efficiency of a compressed dry air system. All compressor types have lower efficiencies when operating at partial load compared to full loads. Since it is unlikely that an air compressor will be sized to exactly match full load operating conditions, the control strategy for compressor operation will either allow the part load impacts to be minimized or allow the part load operation to severely reduce the normal operating efficiency of the compressors. The following analysis will indicate the actual operating efficiency of the systems, including the full load system efficiency and the effects of partial load operation control strategy. Table 3-8 presents general data on the compressed dry air system of each fab. Fabs 8, 11, and 12 did not report data on compressed dry air systems.

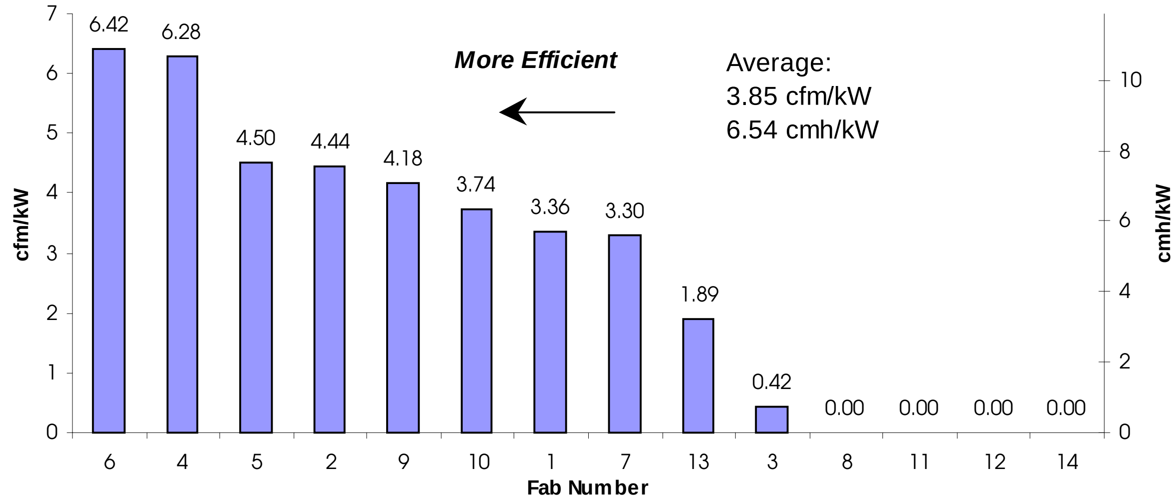
Table 3-8
Compressed Dry Air System Data

Fab Number	Average Measured Electric Load	Average Measured Flow Rate	
	kW	CFM	CMH
1	280	940	1,596
2	765	3,393	5,762
3	333	141	240
4	250	1,571	2,668
5	378	1,700	2,887
6	405	2,600	4,415
7	323	1,065	1,808
8			
9	317	1,325	2,250
10	300	1,123	1,907
11			
12			
13	200	378	642
14		1,718	2,917

Note: Blank cells indicate data was not submitted.
Data appears as submitted by respondent.

Results

Efficiency of a compressed dry air system can be expressed as the cubic feet per minute of air flow per kW of electrical input to the compressors. Large compressors, of the type used in fabs and other large industrial facilities, typically have an efficiency of 4.0 to 5.5 cfm/kW (6.8–9.3 cmh/kW). This correlates well with the data in Figure 3-20, which shows an average efficiency of 3.85 cfm/kW (6.54 cmh/kW). Fab 6 has an efficiency of 6.42 cfm/kW (10.90 cmh/kW), which is high for standard technology. Fab 3 has an efficiency of 0.42 cfm/kW (0.71 cmh/kW), which is unusually low for healthy, operating compressors.



Note: Data labels are in cfm/kW. Fabs 8, 11, 12, and 14 did not report kW and flow, and are not included in the calculation of the average.

Figure 3-20
Compressed Dry Air System Efficiencies

Figure 3-21 illustrates the annual energy required to produce compressed dry air per unit of production for each fab. The average value for this metric is 0.011 kWh per unit of production. Fabs 8, 11, 12, and 14 did not report energy use for compressed dry air. The top performing fabs were fabs 5, 1, and 4.

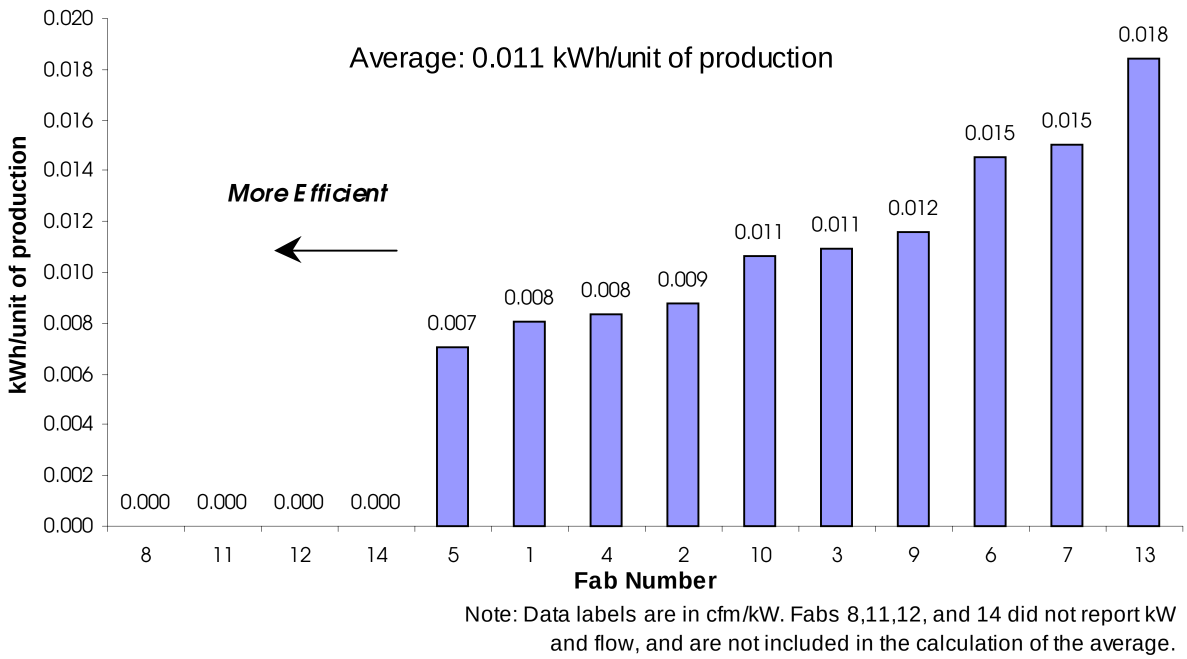


Figure 3-21
Compressed Dry Air System Energy Usage Normalized by Unit of Production

Compressed Dry Air Systems Top Performers—Detailed System Information and Best Practices

Fab 5

- **System Description**

Fab 5's compressed dry air system has an average measured electrical load of 378 kW and an average measured flow rate of 1,700 cfm (2,887 cmh). The fab's compressed dry air system is a co-production system, which means that compressed dry air and nitrogen are produced together from the one main compressor. From this main compressor, the compressed dry air production rate accounts for about 50% of the total suction rate. There are four main compressors, each of which supports five production and two research fabs.

The site consists of multiple fabs served by multiple compressed dry air/nitrogen plants. The plants are interconnected but are normally operated independently with the connection valve closed. The fab surveyed in this study is served by one of the plants, which provides nitrogen and compressed dry air to two fabs at this site.

The system uses centrifugal dry air compressors with a design capacity of 1,950 kW and a design flow rate of 9,717 cfm (16,500 cmh). The dew point specification is -166°F (-110°C). The compressor sequencing is controlled manually. The electrical load is always constant. A relief valve automatically controls the supply pressure at the discharge side of the compressor. The suction rate of the compressor is manually controlled by a guide vane. There is one main centrifugal compressor and one reciprocating waste gas recirculating compressor, both of which are typically operating at all times.

The compressed dry air plant uses desiccant dryers with a design capacity of 9,835 cfm (16,700 cmh). The actual operating pressure provided by the air compressors at the plant is 931 kPa, or 135 psi.

- **Data Collection Methodology**

Both compressed dry air and nitrogen are supplied from the same compressor system and could not be independently electrically metered. The overall compressor electrical load was measured and the electrical use for compressed dry air and nitrogen was determined based upon the gas flow rate for each service out of the compressor. In addition, although the compressed dry air was measured at the fab submitted for this survey, the nitrogen system was not equipped with an existing metering system and was measured at an identical fab at the same location with the same production rate. The flow meters are hot wire anemometers installed when the fab was built in 1994. They have not been recalibrated since installation.

- **Conclusions**

This fab's performance is due to a combination of lower than average nitrogen/compressed dry air efficiency with significantly lower than average compressed dry air and nitrogen use. The low efficiency is probably due to the partially loaded operation of the compressor system (it runs at approximately 50% of its design capacity). Nitrogen is used for typical purposes such as vacuum pumps, wafer drying, and boat washing. The fab has not implemented any program to reduce nitrogen consumption or compressed dry air use.

Fab 4

- **System Description**

Fab 4's compressed dry air system has an average measured electrical load of 250 kW and an average measured flow rate of 1,571 cfm (2,668 cmh). The system uses screw dry air compressors with design capacity of 972 kW and design flow rate of 132.2 cmm (280 kscfh). The dew point specification is -98°F (-72°C). The compressor sequencing, controlled by an automatic device, is based on pressure. Typically, all seven compressor sets operate at the same time. The operating pressure provided by the air compressors at the plant is 107 psi (738 kPa).

- **Data Collection Methodology**

The air compressors and supporting systems were directly measured with portable instrumentation that is calibrated annually. The air flow was measured with a flow meter provided by Atlas, the compressor manufacturer. Electrical measurements were trend-metered, and air flows were spot-metered.

The system appears to have been accurately metered for both electrical use and air production. The original data submitted did not include the cooling water energy, which added 21% to the electrical load of the compressors. Correcting the energy use data dropped the efficiency value to 5.2 cfm/kW (8.8 cmh/kW) for this system, which is still one of the best efficiencies in the survey.

- **Conclusions**

Facility engineers at fab 4 believe that the fab performed well in this area because it is designed more efficiently than others. The fab uses process cooling water instead of a cooling tower to cool the compressors. This decreases the outlet air temperature from 93 to 77°F (34 to 25°C). Therefore, the water consumption is decreased and the number of operating dryers can also be reduced.

Fab 3 also reported higher than average consumption of compressed dry air with 3.2 cubic feet (0.09 m^3)per unit of production. This site compensates for high consumption with high efficiency. If the usage at this site could be reduced to the same level as the fab average, it would significantly increase the performance of the fab system.

Fab 2

- **System Description**

Fab 2's compressed dry air system has an average measured electrical load of 765 kW and an average measured flow rate of 3,393 cfm (5,762 cmh). The compressed dry air plant uses screw compressors. The compressor design capacity is 1,280 kW, and the compressor design flow rate is 10,000 cfm (16,981 cmh). The dew point specification is -120°F (-84°C).

An automatic sequencing procedure controls the seven compressors based on a pressure setting point. Typically four compressors operate at one time. The compressed dry air plant uses desiccant dryers with a design capacity of 4,122 scfm (7,000 scmh). The air compressors at the plant provide an actual operating pressure of 125 psi (862 kPa).

- **Data Collection Methodology**

The electrical data for the air compressors were spot-metered with hand-held portable metering instruments. Air compressors typically operate by continuously loading and unloading to meet the actual facility load. Spot metering therefore may not accurately capture the average operation of the air compressors. The fab's measurement techniques for air flows were not available; however, air flows were likely measured by permanently installed metering systems. Calibration data on these system are also not available.

- **Conclusions**

The significant discrepancy between design and actual efficiency indicates that either the usage is higher than measured or significant savings potential exists with the fab's compressed dry air systems. The actual system efficiency per the submitted measurements is 56% of the design system efficiency. This may be a result of running the compressor or compressors at low load conditions instead of controlling multiple compressors to ensure that some compressors are base loaded with a trim compressor.

Process Cooling Water System

Description

Process tool operation generates internal tool heat that must be removed for proper tool operation. Some tools are equipped with individual chillers that provide cooling. Other tools use a process cooling water system that provides chilled water at 60–65°F (16–18°C). [12] Process cooling water systems generally consist of a distribution piping system, a circulating pump, and a heat exchanger to isolate the process cooling water flow from any contaminant in the main chilled water loop. The cooling for process cooling water is usually supplied by the central plant system and is not included in the process cooling water system efficiency analysis. General data about the process cooling water systems of participating fabs are given in Table 3-9.

Table 3-9
Process Cooling Water System Data

Fab Number	Average Measured Electric Load	Average Measured Flow Rate		Supply Temp.		Return Temp.	
	kW	GPM	LPM	F	C	F	C
1	150	2,034	7,700	63	17	70	21
2	475	6,548	24,783	63	17	75	24
3	280	2,598	9,832	65	19	73	23
4	245	2,682	10,150	64	18	71	22
5	289	3,567	13,500	68	20	76	25
6	73	1,752	6,631	56	13	65	18
7	115	1,789	6,770	55	13	64	18
8	215	2,818	10,667	64	18	70	21
9	35	500	1,893	65	18	71	22
10	112	1,300	4,921	60	16	65	18
11	200	1,780	6,737	60	16	62	17
12	69	3,403	12,880	50	10	56	13
13	80	705	2,670	61	16	72	22
14	52	3,100	11,734	54	12	58	14

Note: Data appears as submitted by respondent.

[12] Some fabs use water supply temperatures as low as 50°F.

Results

Figure 3-22 shows the efficiencies of the process cooling water pumping systems. The three most efficient fabs are fabs 14, 12, and 6. These fabs have process cooling water system efficiencies of 59.6, 49.6, and 24.0 gpm/kW (225.6, 187.7, and 90.8 lpm/kW), respectively. The median value is 18.96 gpm/kW (71.75 lpm/kW).

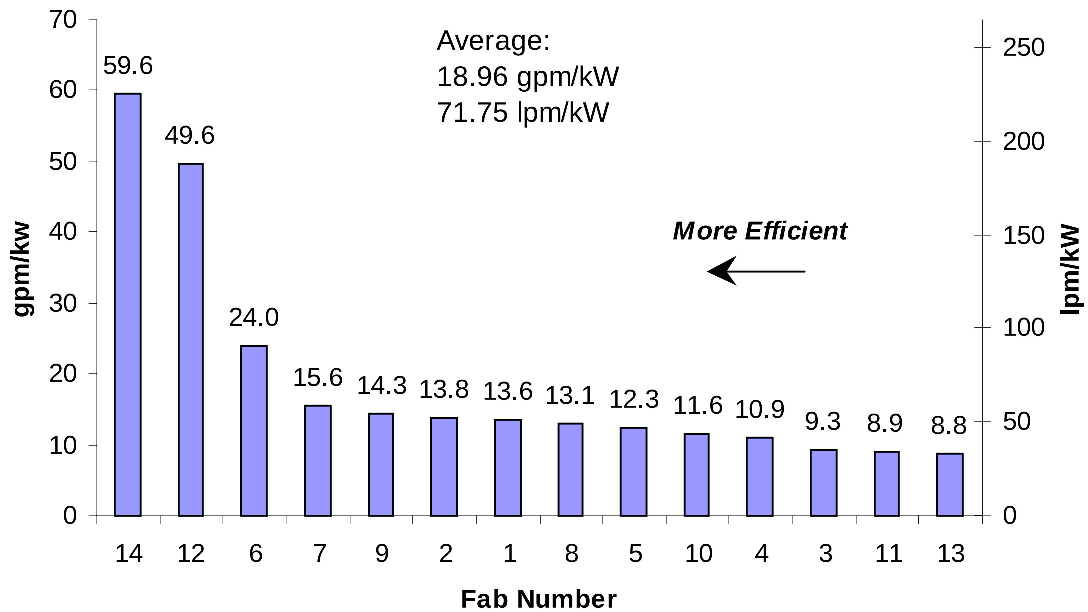


Figure 3-22
Process Cooling Water Pump Efficiencies

Figure 3-23 illustrates the annual process cooling water pumping energy use per unit of production. The median value for this metric is 0.0052 kWh per unit of production.

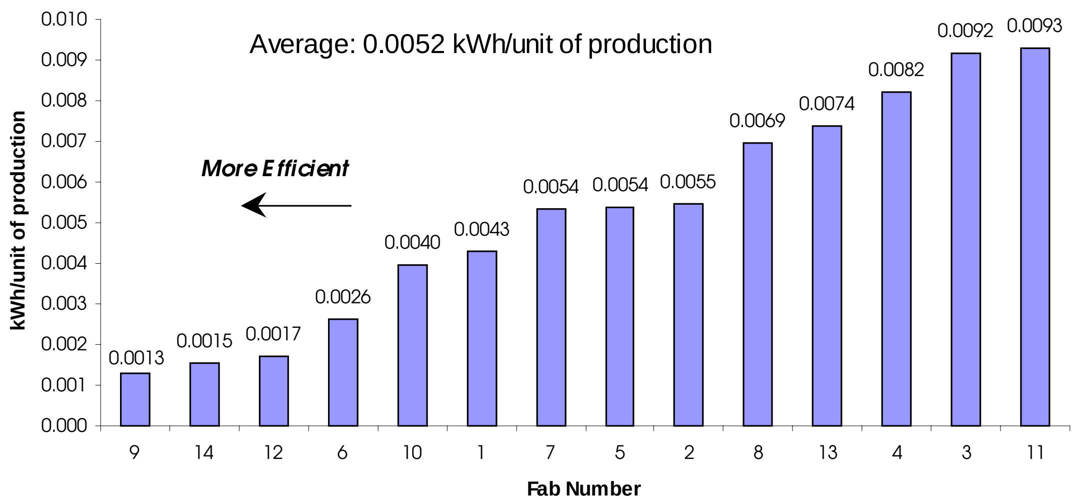


Figure 3-23
Process Cooling Water System Energy Usage Normalized by Units of Production

Fab 9 requires the least pumping energy per unit of production while fab 11 uses the most. The data shown in Figure 3-1 indicate that the process cooling water system is a relatively small load, and although it can be a good target for energy savings, it will not significantly affect the fab's overall energy use.

Process Cooling Water Systems Top Performers—Detailed System Information and Best Practices

Fab 9

- **System Description**

Fab 9's process cooling water system has an average measured electric load of 35 kW and an average measured flow rate of 500 gpm (1,893 lpm). The supply temperature of the water is 65°F (18°C); the return temperature is 71°F (22°C). The actual average measured flow rate is 1,100 gpm (4,164 lpm). One process cooling water system has three 75 hp (56 kW) constant speed pumps, two of which run all the time supplying 500 gpm (1,893 lpm). The other system has two 125 hp (93 kW) variable speed pumps, both running at 40% supplying 600 gpm (2,271 lpm).

A previous study at the site found that process cooling water is supplied through main trunk lines running from the facilities building. The return system is collected in a central holding tank for redistribution. The temperature difference at the heat exchanger was measured at 6°F (-14°C) using the existing facility monitoring system. Total flow through the system was measured at 1,433 gpm (5,424 lpm) with 600, 500, and 333 gpm (2,271, 1,893, 1,260 lpm) allocated to the three fabs at this site. Only two of these fabs were fully operational during the previous study. The third fab was excluded from the study.

- **Data Collection Methodology**

The data for this fab was not originally metered for this survey and was adapted from a previous survey. The original survey metered the energy use for all three fabs at the site, but one of the fabs was being populated with tools and was not in full production. To include this site in this survey project, the data for the entire facility were divided to allow comparison of a fully operational fab.

Flow measurements used a Panametric ultrasonic flow meter and inline flow meters located on each tool subsystem. Power metering was performed with a Square D power monitoring system and Dranetz PP1 portable metering equipment.

Before the sub-main takeoffs, at the beginning of each appropriate section of the fab, total flow was measured at the main supply headers. Return flows were also measured to corroborate supply readings.

- **Conclusions**

Conversations with the facility staff indicate that the original data for this system included only the flow and energy use for one of the two fabs studied at this site; however, both fabs were included in the data used to calculate the units of production. Correcting the process cooling water system data to represent the two operating fabs would increase the flow to 1,100 gpm (4,164 lpm) and the electrical demand to an estimated 121 kW. The resulting kWh per unit of production metric (0.0045 kWh/unit of production) would position fab 9 as slightly better than the average. The resulting system efficiency metric of 9.1 gpm/kW (34.4 lpm/kW) would position the fab as slightly below average in system efficiency.

Fab 14

- **System Description**

Fab 14's process cooling water system has an average measured electric load of 52 kW and an average measured flow rate of 3,100 gpm (11,734 lpm). The supply temperature of the water is 54°F (12°C); the return temperature is 58°F (14°C). The system is currently operating at approximately 70% of design flow rate.

- **Data Collection Methodology**

The fab is equipped with both electrical metering and flow metering equipment, which was used to monitor performance of the system. The most recent calibration date for the equipment was unavailable. Insufficient information is known about the metering system to comment on the accuracy of the metering; however, with the exception of measuring the differential temperature, the process cooling water system is one of the easiest systems to measure in the survey.

- **Conclusions**

The system appears to be normal in design except for its significant oversize potential. This fab was slightly more efficient than average in cooling load per unit of production; however, it excelled in pumping efficiency. All the systems in this fab were significantly oversized to ensure they would handle any possible development scenarios.

Oversizing the process cooling water pumping system resulted in lower head loss and increased pumping efficiency. The system is otherwise fairly typical with a variable speed centrifugal pump designed at 900 gpm (3,407 lpm), 250 feet (76 m) of head, and 100 hp (75 kW). The heat exchangers are all flat plate type heat exchangers. Operating within these design parameters would probably have moved this system from one of the top performing fabs to one of the lower performing fabs.

Fab 12

- **System Description**

Fab 12's process cooling water system has an average measured electric load of 69 kW and an average measured flow rate of 3,403 gpm (12,880 lpm). The supply temperature of the water is 50°F (10°C); the return temperature is 56°F (13°C).

The designed differential pressure of the process cooling water distribution pumps is 47 psi (324 kPa) at 3,884 gpm (14,701 lpm). Process cooling water is automatically controlled at the tool level for patterning, thermal, thin films, dry etch, metrology, chemical mechanical polishing, ion implant, and wafer cleaning tools.

- **Data Collection Methodology**

Detailed information on the data collection methodology employed at fab 12 is unavailable.

- **Conclusions**

Facility engineering staff at fab 12 believe that the fab performed well in this area because of the following system upgrades, which were completed within the last two years:

Motors were upgraded from direct drive motors to variable frequency drives (VFDs)

Heat exchangers were upgraded from shell and tubes to plate and frame heat exchangers

Piping was upgraded from PVC to stainless steel

Because of these upgrades, the pressure drop across the heat exchangers decreased from 10 psi to 2 psi, and the pressure drop across filters decreased from 7–10 in. H_2O to 3–5 in. H_2O.

Ultrapure Water System

Description

DI water or UPW is used for cleaning wafers during the manufacturing process. Pumps are the primary users of energy in these systems, but components of heating and cooling may also contribute to the load. There are three typical methods for DI/UPW heating.

The first method involves a quartz type electrical heating system directly at point of use. Another method is heat recovery from the chiller systems. Heating from the chillers will increase the energy consumption level of the chillers slightly, but it is considerably more efficient than a direct electric heat system like the quartz heaters. The last method is a central fuel fixed boiler system. In each case, the energy for heating DI/UPW is in a different system within the fab. Determining the total heating load was not included in this study. General information about DI/UPW systems of participating fabs is shown in Table 3-10.

Table 3-10
UPW Systems Data

Fab Number	Measured Average Process and Pumping Electric Load	Average Measured Flow rate		Average Measured Consumption		Supply Temperature		% UPW Reclaimed for Non-Fab Process	% UPW Reused for Fab Process	Annual Heating Load (if required)	Annual Cooling Load (if required)	
	kW	GPM	LPM	GPM	LPM	F	C	%	%	mmBtuh	Ton-hours of refrig.	kWh
1	300	243	920	243	920	68	20	4%				
2	282	1,739	6,583	528	2,000	73	23	60%	70%			
3	428	1,156	4,375	317	1,200	72	22	73%	12%			
4	532	572	2,166	293	1,108	77	25		80%			
5	1,700	793	3,002	620	2,347	77	25	75%			500	1,758
6	493	700	2,650	350	1,325	71	22					
7	193	568	2,150	255	965	75	24	35%	5%			
8	1,100	793	3,000	608	2,300	68	20	20%	36%	72,502	3,942,000	13,859,947
9	493			350	1,325	70	21					
10	200	1,050	3,974	366	1,385	75	24	50%				
11	650	800	3,028	475	1,798	70	21	12%				
12	385	1,400	5,299	700	2,650	68	20		5%	87,600		
13	150	295	1,117	194	733	70	21		30%			
14	605	475	1,798	475	1,798	70	21			55,801	727,080	2,556,390

Note: Blank cells indicate data was not submitted. Data appears as reported by respondent.

Results

UPW system efficiencies for project participants are shown in Figure 3-24. The average value for UPW system efficiency is 2.24 gpm/kW (8.48 lpm/kW), although this metric varies considerably.

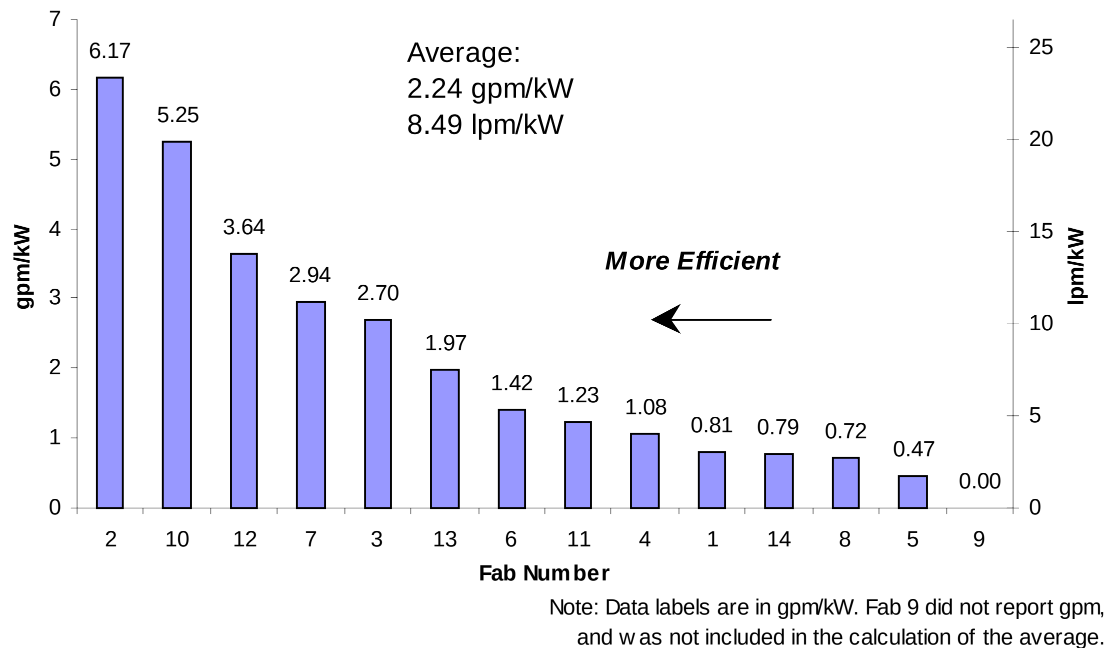


Figure 3-24
UPW System Efficiencies

Figure 3-25 shows the annual UPW production energy use per unit of production. The average value for this metric is 0.017 kWh per unit of production. Fabs numbers 2, 10, and 12 consume the least energy to pump UPW per unit of production while fabs 5 and 8 consume the most.

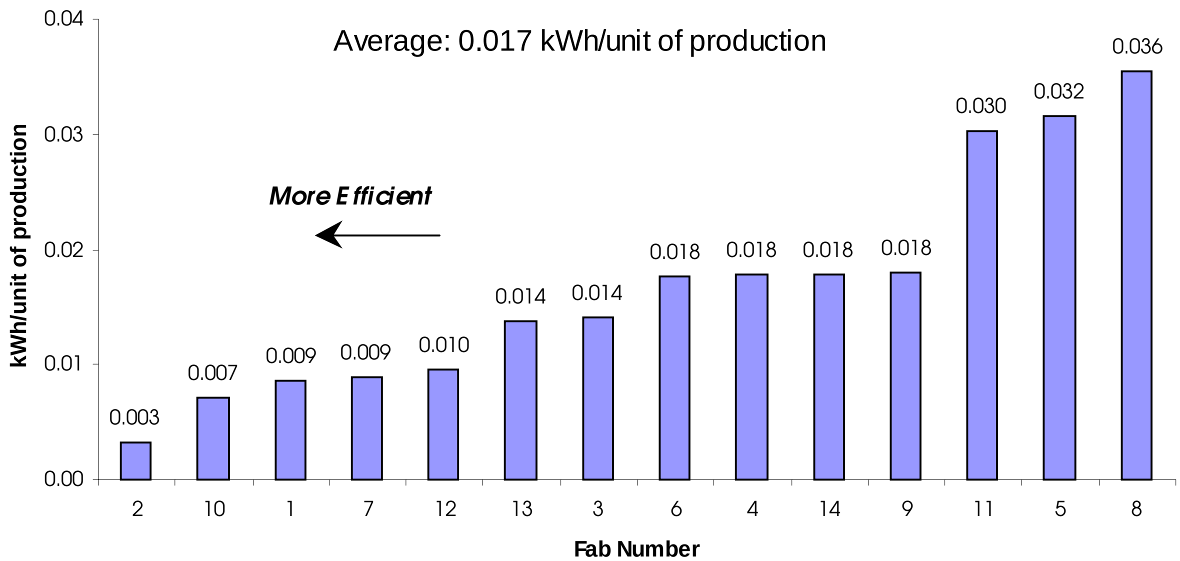


Figure 3-25
UPW System Energy Usage Normalized by Units of Production

UPW Systems Top Performers—Detailed System Information and Best Practices

Fab 2

- **System Description**

The measured average process and pumping electric load of fab 2's UPW system is 282 kW, and the measured average flow rate is 1,739 gpm (6,583 lpm). The measured average consumption is 528 gpm (2,000 lpm). The supply temperature of UPW is 73°F (23°C). 70% of the UPW is reused for fab processes, and 60% is reclaimed for non-fab processes.

The fab's UPW system uses a combination of cation/anion filters, reverse osmosis, and mixed-bed filter. Eighty-five percent of the total system kW is due to pumps. The five highest pressure pumps in the system range from 59–130 psi (407-896 kPa). The horsepower (kilowatt) of these pumps range from 29.49–88.47 (21.99-65.97). Trimming impellers is the most common control method on these pumps; however, the control method for the highest pressure pump (130 psi) (896 kPa) is pump staging. The actual operation production of the UPW system is 516 gpm (1,953 lpm) compared to the design production of 1,000 gpm (3,785 lpm).

- **Data Collection Methodology**

The metering for both the electrical and flow measurements was performed with high quality instrumentation.

- **Conclusions**

Fab engineering staff believe that the fab performed well in this area because it was designed more efficiently than others, makes a product that requires less energy in this category than others, and uses innovative energy management procedures. The following system performance upgrades were made in the past several years:

  – The system was designed with the mixing tank after the mixed media filter, instead of the raw water tank in front of the mixed media filter. This reduces operating pressure and prevents piping breakage.

  – The cation/anion regeneration program was modified to reduce regeneration time and increase system available time.

  – The mixed-bed filter regeneration program was modified to reduce regeneration time and increase system available time.

  – A larger deionized storage tank was installed to extend supplying time for UPW if the pretreatment system were to shut down.

The system excelled in both reduced UPW use and in the efficiency of producing UPW. The reduced use is likely due to tool modifications or tuning, but information was not available to determine what actions took place. The higher efficiency appears to result from a combination of lower than normal head pressures (peak pressure was 130 psi (896 kPa)), which reduces pump energy, combined with trimming pump impellers and staging pumps.

Fab 10

- **System Description**

The measured average process and pumping electric load of fab 10’s UPW system is 200 kW, and the measured average flow rate is 1,050 gpm (3,974 lpm). The measured average consumption is 366 gpm (1,385 lpm). The supply temperature of UPW is 75°F (24°C); 50% of the UPW is reclaimed for non-fab processes. UPW is produced in the fab’s UPW building and is distributed to the fab by plastic piping designed for high purity fluids. Fab operating procedures call for UPW flow to be maintained at around 400 gpm (1,514 lpm) in continuous circulation.

- **Data Collection Methodology**

The data for this fab were not originally metered for this survey, but adapted from a previous survey. The original survey metered the energy use for the fab, but only one-half of the fab was in production. As a result, many of the systems were oversized for the actual load at the time, but would not maintain the same efficiency level when the entire fab was populated with tool and placed in operation. Actual energy use was allocated between the operating portions of the fab and the non-operating portion of the fab, but the impacts of a dramatic increase in total load on the support systems as fab production increased was not included in the measured values.

- **Conclusions**

The high performance of the UPW system at fab 10 results from a combination of high efficiency systems and additional efficiency because of partial operation of the fab. This is one of the newest fabs in the survey. More detailed information about this system was not provided by facility staff.

Fab 7

- **System Description**

The measured average process and pumping electric load of fab 7's UPW system is 193 kW, and the measured average flow rate is 568 gpm (2,150 lpm). The measured average consumption is 255 gpm (965 lpm). The supply temperature of UPW is 75°F (24°C); 35% of the UPW is reclaimed for non-fab processes, and 5% is reused for fab processes.

The UPW system uses a combination of reverse osmosis, multimedia, carbon, UV, mixed bed, and UF; 84% of total system kW is due to pumps. The five highest pressure pumps in the UPW system range from 50 to 309 psi (345-2130 kPa) and from 15 to 46 kW. The use of trim impellers is the most common control method on these pumps; however, control methods for the highest pressure pump (reverse osmosis high pressure – 309 psi (2130 kPa)) are throttling and pump staging. Actual operation production of the UPW system is 255 gpm (965 lpm) compared to the design production of 440 gpm (1,665 lpm).

- **Data Collection Methodology**

No additional information on the data collection methodology is available for this fab.

- **Conclusions**

Facility engineering staff at fab 7 believe that savings are due to process optimization, such as timing of chemical dosing and adjusting pH and temperature. The following measures were recently taken in parallel and reduced UPW use in the fab by 30%:

   – Reduced the flow rate of UPW to tools, especially hoods overflow rate
   – Reduced rinse/cycle time
   – Changed operating concept (i.e., no rinsing of idling tools)
   – Performed audit to ensure idling tools are not wasting UPW for overflowing

Despite this fab's concerted efforts at reducing UPW use, the fab's status as a top performer appears to be more the result of efficiency obtained in the UPW plant than from reduced consumption of UPW. UPW usage is about average among the fabs studied, but the efficiency is about 50% better than average.

Energy Use by Process Area Tools and Support Systems

This section describes general findings and presents significant data for aggregated tool loads in key process areas by the type of energy consumed. Of nine process areas considered for detailed study, the key process areas were defined as follows:

- Patterning
- Wafer cleans
- Thin films
- Dry etch
- Thermal
- Implant

These process areas were selected for detailed study based on findings of the pilot site studies that indicated they were the largest energy-consuming process areas in the fab.

The participating fabs submitted data on the number of tools in each process area in their fabs and, for certain tools, recorded both the manufacturers' design specifications and the actual operating loads or flows for

- Electricity (load), expressed in kilowatts
- Process cooling water (flow), in gallons or liters per minute
- UPW (flow), in gallons or liters per minute
- Exhaust (flow), in standard cubic feet per minute (cubic meters per minute)

Each of these load or flow rates was analyzed to determine which measured loads or flow rates were within design parameters and which were not. Significant differences between designed and measured load and flow rates could signal opportunities for reduced design and therefore lower cost of future tools and their support systems.

For process cooling water, UPW, and exhaust, the study team distinguished among flow rates that were within, above, and below 10% of design parameters. Measured flow rates within 10% of design parameters are considered to be within the typical accuracy of test and balance work and are assumed to be appropriately balanced.

For electricity loads, this method of categorization was determined to be inappropriate, as electrical systems are normally designed to handle maximum loads that are rarely, if ever, experienced under normal operating conditions. Further, tool electricity typically is controlled by fab processes, not by operators, unlike other areas of tool consumption (process cooling water, UPW, and exhaust), which typically are controlled by the user during tool setup. Instead of presenting the electricity data in terms of within, above, and below 10% of design capacity, the project team decided to present the lowest, second lowest, median, second highest, and highest designed-to-measured load ratios.

While data for specific tool manufacturers and models were collected, they are not described here. Appendix D contains summary charts showing designed and measured loads and flow rates for individual tools organized by process area. The charts allow readers to see what tools, in what process areas and under what operating conditions, have been designed to accommodate loads or flow rates that are higher than the load or flow rates actually experienced during tool operation. The charts provide a preliminary indication of which tools or tool support systems could be redesigned to reduce their energy consumption without affecting tool operation.

However, conclusions about energy-efficient tool redesign efforts should be drawn cautiously because of 1) the small number of measurements taken for any individual tool, 2) inconsistencies in measurements resulting from self-reporting the data, 3) the diversity of applications for which a particular tool is used in operating fabs, and 4) variations in the physical specifications of a particular tool both within and among fabs, such as the number of process chambers. These conclusions and limitations are described more fully in Appendix D.

Given these limitations, it is impossible to make firm conclusions about the potential for energy efficiency improvements on any particular tool. However, by aggregating tool data by process area, the study team was able to draw more general conclusions about energy savings opportunities by process area.

General Findings

Tools selected for measurement are used in six of the nine process areas involved in semiconductor fabrication. The six categories selected for individual tool measurements (dry etch, thin films, thermal, patterning, wafer cleaning, and ion implant) represent nearly 77% of all the tools within a fab. Figure 3-26 shows how the tools are allocated to process areas within the fabs studied.

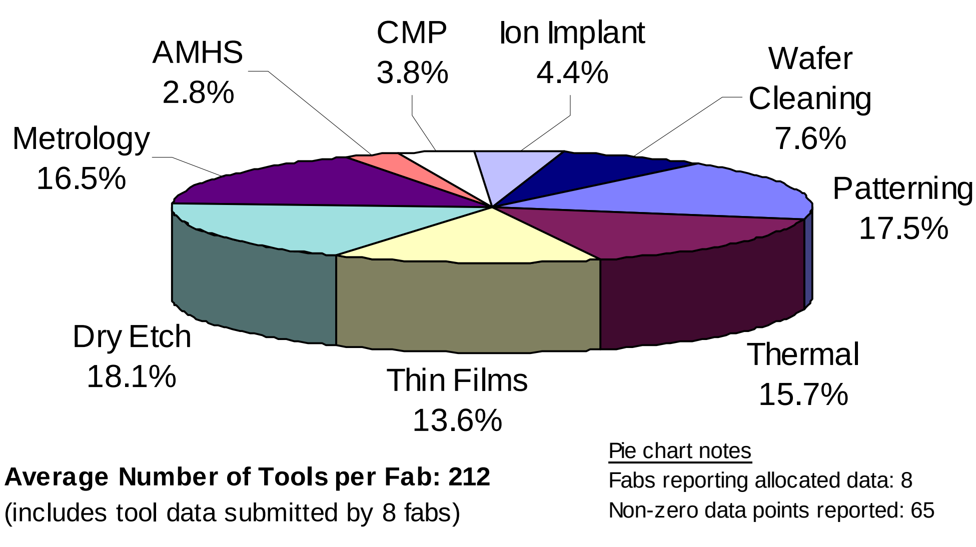


Figure 3-26
Weighted Average Allocation of Tools to Process Areas

The project team calculated the average distribution of process tools using the following methodology:

1. Each fab submitted the number of tools present in their fab in each of the nine process areas.

2. For each fab, the distribution of tools was calculated on a percentage basis among the process areas.

3. To weight the distributions by the units of production for each fab, the percentage of tools in each process area was multiplied by the units of production for that fab and the results presented in a pie chart.

The study team used this approach of normalizing the number of tools in each process area to account for the effects of production volume and product complexity on average tool distribution. This approach has the effect of treating more productive fabs (as defined by their annual units of production) more heavily in the analysis.

This methodology is essentially the same as that used in Figure 3-1; it is used consistently in all pie charts in this report. The normalized pie charts shown in the electricity, process cooling water, UPW, and exhaust sections that follow were created using the same methodology.

Electricity Usage

Designed-to-Measured Loads

Designed and measured electricity loads for tools aggregated by process area are shown in Table 3-11. The design loads are typically specified by the manufacturer of the process tool. The data may be helpful in predicting fab energy loads by process area and for identifying process areas with a high potential for electricity savings opportunities.

The highest median designed-to-measured electricity load ratios occur in the thermal (5.0), wafer cleaning (4.8), and dry etch (4.6) process areas. This means that the median tool measured in each of these areas was designed to handle electrical loads approximately four to five times the average load measured during actual tool operation.

Thermal loads are electrical heating loads, such as quartz heaters for DI and UPW; the wafer cleaning tools may also have electric heating elements. The high ratios may be due to deliberately oversizing the heating elements or to installing multiple heaters in a single tool. The oversizing level could mean that the designers of new fabs are designing all the facility systems to handle a much larger load than would be found under real-world conditions. Oversizing facility equipment can result in additional initial capital and installation costs. These costs may outweigh potential savings resulting from other energy reduction opportunities in a fab.

The lowest median design-to-measured load ratios apply to the ion implant and patterning tools.

Table 3-11
Designed-to-Measured Electricity Load Ratios by Process Area

Process Area	Total # of Tool Measurements	Electrical Load (kW)				
		Lowest	2nd Lowest	Median	2nd Highest	Highest
Patterning	13	0.3	1.0	2.7	5.0	7.9
Thermal	18	2.6	2.8	5.0	24.7	173.7
Thin Films	35	1.4	1.5	3.8	7.3	8.1
Dry Etch	37	2.0	2.3	4.6	11.2	225.6
Ion Implant	20	1.0	1.4	2.7	5.8	6.3
Wafer Cleans	28	0.2	1.5	4.8	43.6	225.6

Normalized Data

Tool electricity use normalized by unit of production is shown in Figure 3-27. Tools in dry etch, thin films, and thermal account for nearly 64% of all tool energy use. Thin films alone account for over 24% of tool electricity use.

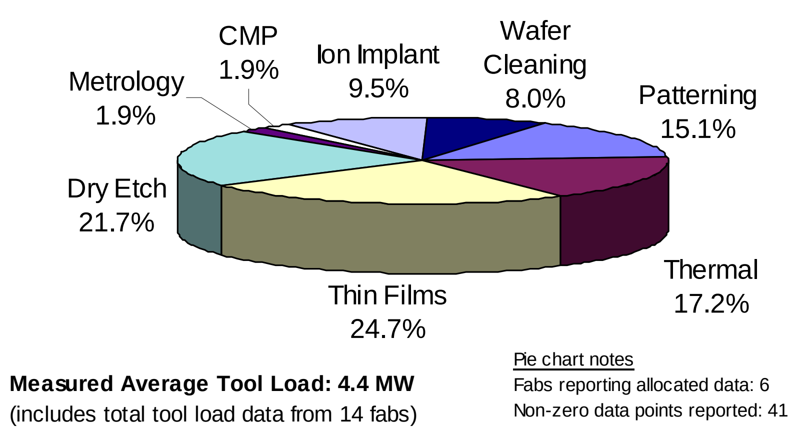


Figure 3-27
Weighted Average Electricity Usage by Process Area[13]

[13] This pie chart was derived from allocated tool data submitted by 6 of the 14 participating fabs. The measured average tool load reported in the figure was derived from total tool loads submitted by all 14 fabs. Dividing the measured average tool load (4.4 MW) by the average fab electric load (12.7 MW, reported in Figure 3-1) reveals that the average fab allocates 34.7 percent of its electric load to tools. This is different than the conclusion reached in Figure 3-1 and elsewhere in this study, where it is reported that fabs allocated an average of 40.7 percent of their energy to tools. The difference is due to the fact that Figure 3-1 reported a wighted average using fabs' annual units of production as the weighting factor; the result was that fabs with higher production levels were weighted more heavily in the analysis. In contrast, all fabs are treated equally in the analysis resulting in Figure 3-27. Put another way, Figure 3-1 shows an *allocation of energy per unit of production*, while Figure 3-27 shows an *allocation of energy per fab*.

When combined with the data in Table 3-11, the pie chart reveals likely opportunities for reducing high design values among tools in thermal and dry etch. The pie chart shows that these process areas are significant energy consumers while the table shows that the process area tools tend to be designed to handle larger electrical loads than are actually experienced in operating fabs.[14] Therefore, there may be opportunities to reduce the designed electrical loads in these tools in future models (thereby reducing the installation and manufacturing cost of the tools) without affecting tool operation.[15]

Process Cooling Water Usage

Designed-to-Measured Flow Ratios

Designed and measured process cooling water flow rates for each of the six key process areas are shown in Table 3-12. The greatest difference between designed and measured flow rates were recorded in the thermal, patterning, and dry etch process areas. The median designed-to-measured flow rate ratios for these process areas indicate that the tools in these process areas are designed to handle process cooling water flows of 1.5 to 2.1 times the measured load. The other process area tools had average measured flow rates near or slightly below designed flow rates.

Table 3-12
Designed to Measured Process Cooling Water Flow Ratios by Process Area

Process Area	Total # of Tool Measurements	Under 10% of Design	Within 10% of Design	Over 10% of Design	Median
Patterning	7	6	1	0	1.7
Thermal	8	8	0	0	2.4
Thin Films	17	12	2	3	1.2
Dry Etch	22	15	2	5	1.5
Ion Implant	8	5	1	2	1.2
Wafer Cleans	8	4	3	1	1.1

[14] There may also be opportunities in the thin films area, though probably not as great. Although thin films tools are the largest energy users according to Figure 3-27, their designed-to-measured load ratio is not as high as those for dry etch, wafer cleaning, and thermal.

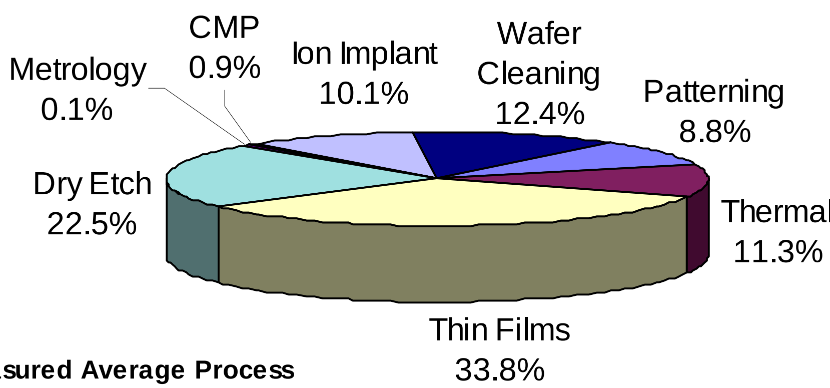
[15] Readers may refer to the tables in Appendix C as an indicator of which tools' electrical systems are designed to handle greater loads than were actually measured, but the data limitations described at the beginning of the appendix prevent the project team from making firm conclusions about individual tools at this time.

One factor that may affect the process cooling water flows is the supply water temperature. Process cooling water supply water temperature ranged from a low of 50°F (10°C) with a return temperature of 56°F (13°C) to a high supply temperature of 68°F (20°C) and a return temperature of 76°F (24°C). Many tool manufacturers give a range of the supply water temperature and a constant flow rate. The amount of cooling delivered by process cooling water flows is a function of the temperature and flow rate. It appears unlikely that the flow rates would stay constant regardless of temperatures, although this cannot be confirmed from the data reported.

The table shows there may be opportunities to reduce the process cooling water system design size and perhaps to economize on designed process cooling water flow rates among tools used in the thermal, patterning, and dry etch process areas.

Normalized Data

Process cooling water usage normalized by units of production is shown in Figure 3-28. The top three process areas by consumption of process cooling water were thin films, dry etch, and thermal. Together, these process areas account for nearly 69% of the process cooling water usage in the fabs studied.



Measured Average Process Cooling Water Flow Rate for Tools:
9,349 lpm (2,470 gpm)
(includes flow data submitted by 14 fabs)

Pie chart notes
Fabs reporting allocated data: 5
Non-zero data points reported: 31

Figure 3-28
Weighted Average Process Cooling Water Usage by Process Area[16]

[16] This pie chart was derived from allocated tool data submitted by 5 of the 14 participating fabs. The measured average process cooling water flow rate for tools reported in the figure was derived from total process cooling water flows submitted by all 14 fabs, and may contain process cooling water flows that are not dedicated directly to tools.

When combined with the designed-to-measured flow rate data from Table 3-12, the analysis reveals the highest likelihood for identifying opportunities for reducing process cooling water piping and pump sizing in dry etch and thermal and among dry etch and thermal tools. These reductions in process cooling water system and tool design requirements could result in capital savings in new or remodeled fabs. These tools consume over 34% of the process cooling water in the fabs studied and on average are designed to accommodate twice the amount of process cooling water flows actually experienced in operating fabs. Other opportunities for energy reduction may exist among thermal and patterning tools, but these areas account for only 11.3 and 8.8%, respectively, of the process cooling water requirements of the fabs studied.[17]

UPW Usage

Designed-to-Measured Flow Ratios

Designed and measured UPW flow rates for four of the six key process areas are presented in Table 3-13.[18] In the thin film area, the flow rates of three tools were measured; one was within 10% of design flow, one was under 10% of design, and the other was over 10% of design. None of the dry etch or ion implant tools measured had measured flow rates within design parameters (although it should be noted that only one ion implant tool was measured). The median designed-to-measured flow ratio among dry etch and ion implant tools was 1.6, meaning that the median tool was designed to accommodate 1.6 times the actual measured flow of UPW. Wafer cleaning tools tended to be more overdesigned, with the median designed-to-measured flow ratio at 1.9.

Table 3-13
Designed to Measured UPW Flow Ratios by Process Area

Process Area	Total # of Tool Measurements	Number of UPW Flows Within Design Range			
		Under 10% of Design	Within 10% of Design	Over 10% of Design	Median
Patterning	--				
Thermal	--				
Thin Films	3	1	1	1	0.9
Dry Etch	8	8	0	0	1.6
Ion Implant	1	1	0	0	1.6
Wafer Cleans	11	9	1	1	1.9

[17] Readers may refer to the tables in Appendix C as an indicator of which tools' process cooling water systems are designed to handle greater flows than were actually measured.

[18] The patterning and thermal areas do not use significant amounts of ultrapure water.

These data indicate a strong likelihood for potential savings by reducing the design parameters of UPW support systems and process area tools in wafer cleaning and, to a lesser extent, in dry etch.[19] Nine of the 11 tools measured in the wafer cleaning process area were designed to accommodate higher UPW flows than are actually experienced in an operating fab.

Normalized Data

Figure 3-29 shows fab UPW consumption by process area. Tools in chemical mechanical polishing (CMP) and wafer cleaning together account for 95% of the ultrapure consumption in the fabs studied.

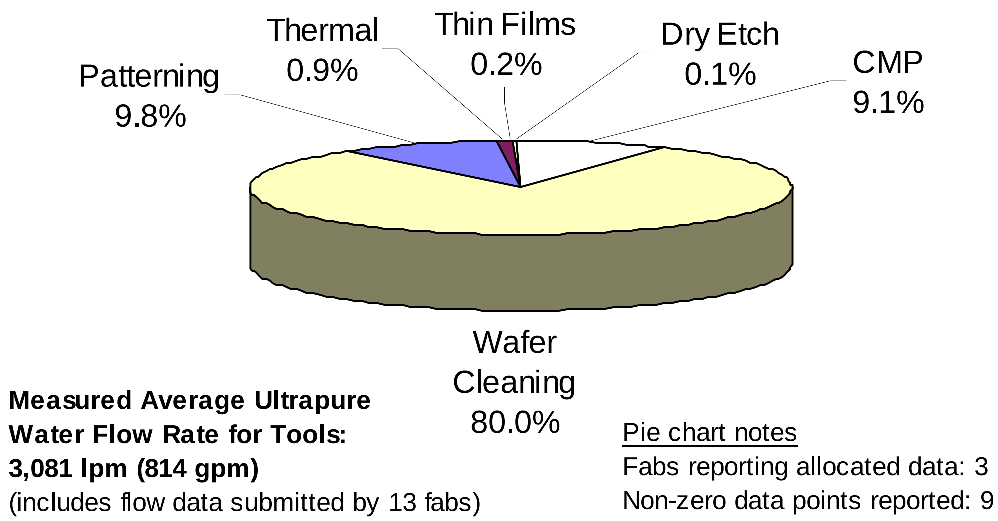


Figure 3-29
Weighted Average UPW Usage by Process Area[20]

When combined with the data on designed-to-measured load ratios in Table 3-13, the analysis reveals a high likelihood for identifying both water use and energy reduction opportunities among wafer cleaning process area support systems and tools. These tools consume nearly 80% of the UPW in the fab and are designed at the median to handle flows that are 1.9 times those actually experienced in the fab.[21]

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[19] The ion implant area has the same median designed to measured load ratio as the dry etch area, but since only one tool was measured in ion implant, conclusions for this area are weak.

[20] This pie chart was derived from allocated tool data submitted by 3 of the 14 participating fabs. The measured average ultrapure water flow rate for tools reported in the figure was derived from total ultrapure water flows submitted by 13 of the 14 fabs, and may contain ultrapure water flows that are not dedicated directly to tools.

[21] Readers may refer to the tables in Appendix C as an indicator of which tools' ultrapure water systems are designed to handle greater flows than were actually measured.

Exhaust

Designed-to-Measured Flow Ratios

Tool exhaust flows are controlled by the test and balance technician who adjusts the exhaust flows. Unlike the other designed and measured loads and flow rates for tools, which may indicate an opportunity to offer adjusted performance data for design purposes, exhaust measurements indicate only how well the tool was balanced to provide the correct air flow.

Table 3-14 shows the designed and measured exhaust flow rates of tools studied by process area. The majority of the tools have measured exhaust flows higher than their design parameters. However, those with exhaust flows below the design range tend to be significantly below design. The data in Table 3-14 indicate that the median exhaust flow ratio is below the design range in the patterning, thermal, and wafer cleaning process areas, within the design range in the ion implant process area, and over the design range in the thin films and dry etch process areas.

Table 3-14
Designed to Measured Exhaust Flow Ratios by Process Area

Process Area	**Total # of Tool Measurements**	**Number of Exhaust Flows Within Design Range**			
		Under 10% of Design	Within 10% of Design	Over 10% of Design	Median
Patterning	6	2	1	3	0.9
Thermal	10	4	0	6	0.8
Thin Films	18	9	2	7	1.2
Dry Etch	21	13	1	7	1.4
Ion Implant	9	4	2	3	1.0
Wafer Cleans	19	7	2	10	0.9

The median designed-to-measured ratio in the dry etch process area is 1.4, indicating that the median tool measured was designed to handle 1.4 times the exhaust flow measured under normal operating conditions. If the measured tool flows are based on actual tool needs or do not indicate a balancing problem because of system modification or setup, this could indicate an opportunity to downsize future dry etch tool exhaust systems. However, this conclusion is difficult to make because only 62% of the dry etch tools measured had exhaust systems that were overdesigned by 10% or more. The remaining 38% of dry etch tools' exhaust systems were either underdesigned or within the normal range of operation.

A similar but even more pronounced situation occurs with tools in the thin films process area. The median designed-to-measured ratio in this process area is 1.2, indicating that the exhaust system of the median tool is designed to accommodate 1.2 times the flow rate actually experienced in operation. However, only 39% of the thin films tools had exhaust flow rates that were higher than design parameters. Most thin films tools, therefore, were within or below design parameters for exhaust flows.

Normalized Data

Figure 3-30 shows exhaust flows of tools allocated by process area. The figure shows that the dry etch, wafer cleaning, and thin films process areas account for nearly 68% of the total tool exhaust in the fabs studied.

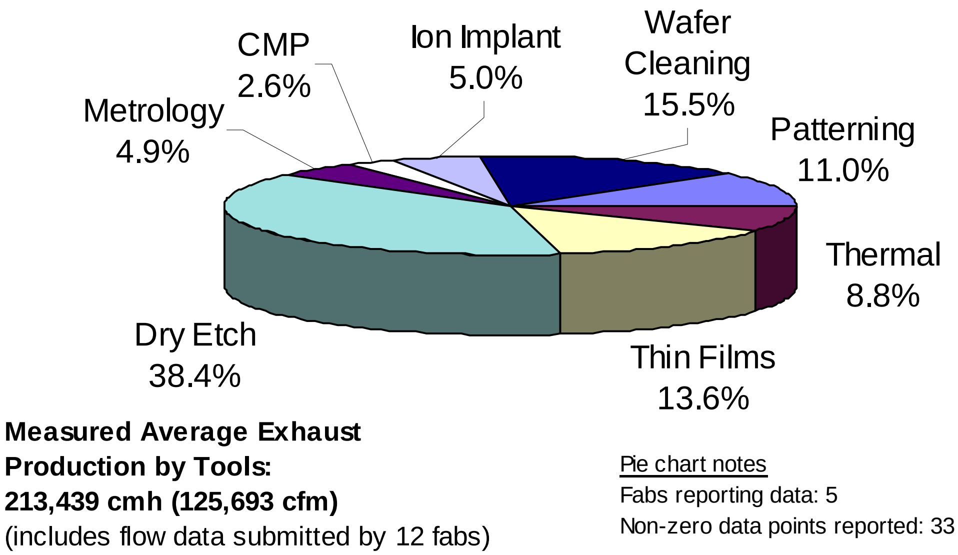

Figure 3-30
Weighted Average Exhaust Production by Process Area[22]

When combined with the data on designed-to-measured load ratios in Table 3-14, the analysis reveals the highest likelihood for identifying system design reduction opportunities among the dry etch and thin films process area tools. These tools account for over 52% of the exhaust flows in the fab, and are designed at the median to handle flows that are 1.4 and 1.2 times the flows actually experienced in the fab, respectively. However, as stated above, opportunities to achieve cost savings through exhaust system redesign efforts may be difficult to come by, since the majority of dry etch tools' exhaust systems measured in this study were handling actual exhaust flows within or higher than designed parameters.[23]

Improving the Efficiency of Process Area Support Systems and Tools

The preceding sections presented data on the designed and measured loads and flow rates of process tools aggregated by process area, and presented data on the allocation of these loads and flow rates within a fab by process area. The loads and flow rates analyzed included electrical

[22] This pie chart was derived from allocated tool data submitted by 5 of the 14 participating fabs. The measured average exhaust production rate for tools reported in the figure was derived from total exhaust flows submitted by 12 of the 14 fabs, and may contain exhaust flows that are dedicated directly to tools.

[23] Readers may wish to refer to the tables in Appendix C as an indicator of which tools' exhaust systems are designed to handle greater flows than were actually measured.

loads and process cooling water, UPW, and exhaust flow rates. The discussion and analysis in each section highlighted the following:

- Process areas in which tools tended to be designed to handle loads and flow rates significantly higher than were actually experienced in working fabs
- Process areas with relatively high allocation of relevant loads or flow rates
- Process areas in which both of these conditions were present for a given load or flow rate

The third item is a set consisting of the intersection of the first two items and can be used to identify the loads, flows, and process areas with the greatest potential to improve overall fab efficiency be redesigning certain process area tools and/or their facility support systems. The table below shows the process areas in which tool electrical loads and process cooling water, UPW, and exhaust flows can most likely be optimized within tool support systems or tools themselves to achieve cost savings.

Process Area	Type of Load or Flow
Dry Etch	Electricity Process cooling water Exhaust
Thermal	Electricity Process cooling water
Thin films	Exhaust
Wafer Cleaning	UPW

The dry etch process area appears to be a candidate for design improvement in electricity, process cooling water, and exhaust use. These constitute three of the four types of loads or flow rates. The dry etch process tools account for 18.1% of the tools in the fabs studied, as shown in Figure 3-26.

The thermal process area appears to be a candidate for design improvement in electricity and process cooling water support systems and tools. Tools in this area account for 15.7% of the tools in the fabs studied.

The thin films process area appears to be a candidate for design improvement in exhaust use only. Tools in this area account for 13.6% of the tools in the fabs studied.

Finally, the wafer cleaning process area is the only strong candidate for design improvement in UPW use. Tools in this area account for 7.6% of the tools in the fabs studied.

Further study on process tools is needed to verify and refine these initial findings.

Process Tools Top Performers—Detailed System Information and Best Practices

Figure 3-7 showed how the participating fabs performed in terms of tool energy use per unit of production. Three of the top performing fabs in this category were selected for follow-up studies and interviews to identify more detailed information about their process tools and to determine why these fabs may have performed more efficiently than their peers. The fabs selected for follow-up study included fabs 9 and 10, the two most efficient fabs studied, and fab 2, the fifth most efficient fab studied in terms of tool energy use per unit of production.[24]

Fab 9

The facility was surveyed as part of a pilot study for International SEMATECH before the worldwide benchmarking study. Many of the original data points collected were aggregate values for the three fabs at the site and did not include metered allocation among the fabs. Inclusion of this site in the survey, without a total resurvey of the facility, required allocation of loads within the fabs based upon best estimates where supporting data were not available. Since the initial survey, the fab operation and tool population have changed significantly and further verification of the initial data (including metered and production data) is not available.

Tool electrical loads at this facility are powered by separate bus switchboards from the facility loads. A power monitoring system has been installed so tool loads are easily identified and separated from facility loads. Total tool loads were measured by metering one tool of each type and multiplying times the number of tools of the type in the fab. The resulting loads were totaled to predict the overall tool load.

Fab 10

Eighty-nine tools at this fab were measured for electricity, UPW, and process cooling water consumption and exhaust flows.

Individual tool subsystems were measured at bus duct breakers or circuit breaker panels for periods ranging from 3–48 hours. Fifteen-minute average demand readings were recorded over these intervals. To adjust all measured data into a 24-hour profile, each set of measurements was reset to begin at midnight. For those systems not profiled for 24 hours, the existing data profile was repeated until a 24-hour period was filled. An average over this 24-hour profile was used as the individual tool kW. This tool kW was then multiplied by the number of similar tools to obtain the total tool kW by building section. Energy use for tools is calculated by multiplying this tool demand by 8760 hours per year and the annual tool production diversity provided by production managers.

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[24] Fab 2 was selected for follow-up study because it was a top performer in nearly every facilities area, and because it had been among the top three fabs in terms of tool energy use when the top performers were identified. Subsequent data revisions submitted by this fab and others changed fab 2’s position to the fifth highest performer in terms of tool energy use per unit of production.

The tools were also measured from dedicated electrical buses that supplied only the tools. The two methodologies had close agreement. The data used for the survey were the bus measurements, which were slightly higher than the individual tool measurements.

This fab is the newest fab in the study and is equipped with the newest tool set. All the tool locations were identified during the original design to maximize efficiency unlike many other fabs in the study, which appear to be continually changing and adding tools.

Fab 2

There are 638 tools in this fab. The process tools were installed on electrical panels separate from the facility equipment. Tool energy use was measured at 14 breaker locations with portable metering equipment.

Measurement of tool operating effectiveness may be the key to identifying why this fab's energy use per unit of production is one of the lowest of fabs represented in this survey. The energy use of many tools does not change significantly between standby operation and processing operation. This significant base load indicates that the energy consumption per unit of production will drop as the number of wafers processed in any given time is increased.

Increasing the production rate of a tool may occur in any of three areas. First, the processing time of the tools may be reduced through modification of tool timing and wafer recipe. Second, the load and unload time of the tool may be reduced to effectively increase the processing time of the tool, increasing tool production. Third, the processing efficiency of the tool may be increased by either reducing the processing energy use or the non-processing energy use to the tool.

Insufficient information is available to determine what factors or combination of factors resulted in the low tool energy use at this facility. This lower usage also likely results in lower energy use by the central plant and recirculating fan systems.

Facility engineering staff at this site believe that the fab performed well in this area because it is a newer fab. They attribute the high efficiency of tools to high wafer output, a high ratio of tools that are in use, and a high average tool operation rate (staff report that tools are run at an average of 90% of full capacity).

Reported Best Practices

Five participants—fabs 3, 5, 9, 10, and 11—submitted energy-related best practices to share with other fabs. Like the other data reported in this study, the best practices information reported here was submitted by fabs participating in the study without peer review and without any secondary audit to determine the extent to which the best practices information submitted is related to the fab's energy efficiency performance.

Table 3-15 presents a summary of the best practices submitted by each fab. The table summarizes best practices by type and shows that most reported best practices relate to the following issues and systems in the fab:

1. Major energy-consuming facilities systems and subsystems, such as the central plant and recirculating and makeup air systems

2. Installation of measurement, control, and monitoring systems

3. Incorporation of energy efficiency into overall facility design and engineering record keeping activities

4. Selection and use energy efficient motors

Table 3-15
Reported Best Practices Matrix

Type of Best Practice	Fab Number					Total
	3	5	9	10	11	
Nitrogen systems	1					1
Cogeneration			1			1
Recirculating and makeup air systems	1	1	1		3	6
Chillers and central plant	2	2		2	1	7
Process cooling water system		1	1			2
Measurement, control, and monitoring systems	1		2	3		6
Design and record keeping		1	3	4		8
Energy efficient motors	2			2	1	5
Lighting	1			1		2
Programmatic			1	1		2

These most commonly reported best practices corroborate other findings presented in this report. For example, the data collected from participating fabs indicated that chillers, makeup air fans, and recirculating air fans together constitute approximately 39% of the energy use in the fabs studied, and participating companies reported 13 best practices that related directly to the operation of these major systems. Four out of the five fabs that submitted best practices specifically referenced the chillers and air systems.

Three of the five fabs submitted best practices relating to installing and using sophisticated measurement, control, and monitoring systems within the fab.

A surprise finding was the high number of design and record keeping procedures submitted as best practices. This category of best practices included internal procedures such as keeping design and engineering drawings on hand as a reference for facilities personnel as well as documenting procedures for analyzing energy use within the fab.

Other, less frequently reported, best practices related to lower energy-consuming facilities systems or subsystems (i.e., nitrogen system, process cooling water system, or lighting systems), energy recovery practices (i.e., cogeneration), and programmatic practices. Programmatic best practices are defined as regularly performed maintenance and monitoring procedures that allow fab engineers to identify problems when they arise.

Fab 3 Reported Best Practices

- Absorption chiller
- Thermal energy storage system
- All motors are high efficiency
- Installation of variable speed drives on all variable flow
- All lighting system are high efficiency
- Control and monitoring management improvement
- Liquid nitrogen recovery
- Air compressor efficiency improvement
- Balance exhaust and process cooling water flows before turning tools over to manufacturing

Fab 5 Reported Best Practices

- The preheat heat recovery loop
- The process cooling water closed-loop cooling tower
- The heat-wheel heat recovery system for the chemical distribution exhaust air
- The free tower cooling system
- Running all makeup air units at partial speed
- Segregated zones with different humidity requirements reducing the low-temperature chiller load

Fab 9 Reported Best Practices

- Minimizing the air turnover and static pressure reduction in a fab will significantly affect the annual energy usage.
- Every facility should have a complete one-line diagram of facility electrical loads available indicating power monitoring locations. This is a very valuable tool for planning and implementing power measurements.
- Tool electrical loads should be powered by separate bus/switchboards from facility loads. Every facility should have a power monitoring system that should be installed such that tool loads are easily identified and separated from the facility loads. This information will assist energy analysis and be useful as fabs change functionality with new processes.
- In facilities where several expansions with multiple design engineering packages have occurred, it is very useful to have complete one-line system diagrams. Diagrams of chilled water, condenser water, process chilled water, reheat water, and boiler water help an “outsider” quickly understand the systems being studied. Circuits to air handlers indicating two- and three-way valves, where applicable, will aid in evaluating the retrofit potential.

- A complete list of mechanical equipment in the facility areas (hot water, chilled water, etc.) is very valuable for understanding what is in the systems and subsystems.
- Potential energy conservation measures need to be identified early in the measurement phase of the project to make sure measurements for energy conservation measures get taken.
- Hot DI water that is generated from a central point and piped throughout the fabs as hot deionized (rather than point of use electric strip heat of DI water) represents a significant opportunity for utilization of waste heat from cogeneration.
- The true requirement of the supply temperature of process cooling water needs to be ascertained. If the process cooling water supply temperature were allowed to be 70°F (21°C) (instead of 65°F [18°C]), cooling towers/plate heat exchangers could be used for process cooling water a much higher percentage of the year.
- Compressed air systems can be analyzed much more easily if an inline air flow measurement device is already installed. Airflow, system pressure response, and kW profiles can then be correlated to determine what is really going on in the compressed air system.

Fab 10 Reported Best Practices

- Multiple tandem chiller sets in parallel
- Electronic metering at substation and motor control center
- Tools and facility points are on separate motor control centers
- Networkable electronic metering at 4160 V substations and 4160 V starters
- Chiller manufacturer’s control system on chillers
- Design of all variable loads as variable flows except direct chiller flows
- Energy efficient motors
- Installation of variable speed drives on all variable flows
- Nitrogen backup of compressed air
- High efficiency lighting systems
- Extremely aggressive predictive maintenance program
- Extensive control and monitoring
- Clean modular design
- Placement of most equipment on a single level

Fab 11 Reported Best Practices

- All major motors are equipped with variable frequency drives. Air handling unit fans, chilled water pumps, DI water pumps, process cooling water pumps, and two out of the eight of the cooling tower fans have variable frequency drives (the other six are step-sequenced based on load). Fan filter units also have variable frequency drives, but mainly for performance reasons rather than for energy savings.
- A mechanical consultant was hired to perform a central plant survey when the condition of the plant changes enough to warrant review. Changes were recommended to the sequence of the air handling unit valves operations to reduce the amount of chilled water flow while increasing delta T. This would put the chiller operation into a more efficient region, reduce pump horsepower, and redistribute AC load among the chilled water chillers and ethylene glycol chillers for more efficient operation. The systems are constrained by limited pipe size rather than by chiller tonnage. Another recommended change was to raise the chilled water system temperature to reduce the amount of reheat required.
- Over-pressurization of the fabs was reduced to save on fan energy used to maintain the positive pressurization required for clean operations. Also reduced was the amount of outside air that needs to be conditioned, which reduces energy consumption. A “global” re-pressurization project was undertaken. The arrangement of many fabs is unique: bay and chase with lesser clean “clean corridors” between. Margin of pressurization clean areas to lesser-clean areas was reduced. Another major benefit was less turbulence produced in the corridors and near doors from the fabs.
- Reducing the amount of air changes in selected fabs by -10% is being explored, which would reduce the air flow velocity in fabs without hurting cleanliness performance. Reduction in turbulence is sought since some fabs have very low ceilings and tall tools.
- The following mostly deals with office/support/lab areas (not necessarily fab): Major projects have HVAC distribution converted to variable air volume with all fan coils added to lab areas using variable frequency drives. Major projects also convert any pneumatic controlled area to DDC controls.

Reported Energy Conservation Measures

As part of the survey, each fab was asked to determine energy conservation measures suitable for their facility. An energy conservation measure is any change in facility equipment or operating procedures that may result in lower energy or facilities costs.

Six fabs submitted energy conservation measures. The total projected savings for each fab are shown in Table 3-16. Each company that submitted energy conservation measures is identified in this section with a letter code (A–F). This coding methodology ensures that reported energy conservation measures cannot be attributed to any other data about fabs shown elsewhere in this report.

Table 3-16
Energy Conservation Measures, Estimated Savings by Fab

Facility	Capital Cost	Estimated Annual Savings	Simple Payback
		US Dollars	years
A	$252,500	$574,180	0.44
B	$2,074,000	$791,278	2.60
C		$1,450,180	
D	$715,000	$5,825,000	0.12
E	$0	$123,649	immediate
F		$2,397,896	
Total		**$11,162,183**	

The total annual savings reported by the six fabs was U.S.$11.1 million; average annual savings was U.S.$1.8 million. Not all fabs submitted estimated energy savings in the same format of capital cost, estimated annual savings, and simple payback. For those fabs that did not, the project consultant either calculated the appropriate values from other submitted data when it was possible to do so or did not report data in the table.

Capital cost is the one-time cost of implementing the energy conservation measure. Estimated annual savings is the reduction in operating costs projected to result from implementing the energy conservation measure. Simple payback is the capital cost divided by the estimated annual savings; it provides an estimate of how many years the energy conservation measure will take to pay for itself.

Five of the six fabs that reported energy conservation measures were 5 years old or younger. These results demonstrate that cost-effective energy conservation measures can be found even in newer fabs.

Detailed tables of the energy reduction opportunities identified by each fab are in Appendix F.

4

CONCLUSIONS AND RECOMMENDATIONS

New Energy Efficiency Metric for Fabs—kWh per Unit of Production

This study pioneers the use of kWh per unit of production as a measure of energy efficiency in fabs and fab systems. The denominator of this metric, units of production, is defined as the product total area of wafer processed annually and the average number of mask layers per wafer. This new metric improves upon existing energy efficiency metrics standard in the industry, such as kilowatt-hours per square inch (square millimeter) of wafer processed, by incorporating manufacturing complexity into the normalization of energy efficiency to production volume.

Not all products of semiconductor manufacturing facilities are equivalent; some produce products that are more complex than others. While the annual production of two fabs may be identical when measured in terms of the total area of wafer processed, production might differ dramatically when manufacturing complexity is also considered. This study captures and quantifies the manufacturing complexity of a fab's products by identifying the average number of mask layers per wafer processed at the fab. The results are significantly different than when mask layers are not included; this finding may have important implications for how the semiconductor industry measures and tracks energy efficiency in fabs.

For example, data obtained from the 14 fabs that participated in this study show that when energy efficiency is measured in terms of kilowatt-hours per square inch (without accounting for manufacturing complexity), newer fabs tended to be slightly less efficient than older fabs. However, when energy efficiency is measured in terms of kWh per unit of production (accounting for manufacturing complexity), newer fabs tended to be more efficient than older fabs. This finding is more consistent with the expectation that fabs are improving energy efficiency over time.

In efforts to benchmark or track fab energy efficiency over time, it may be more appropriate to use the kilowatt-hours per unit of production metric or other metrics that recognize the increasing production complexity of semiconductor products.

Allocation of Electric Energy Consumption to Facilities Systems and Process Tools

Process tools were the largest single consumers of energy in the fabs surveyed, consuming 40.6% of all the energy used per unit of production. Chiller systems were the second largest consumers at 24.9%, while the recirculating air system was third at 11.0%. Together, these systems make up over 76% of all energy used in the fabs studied, per unit of production.

If fab energy engineers are seeking energy efficiency opportunities, these tools and systems would be a logical place to start. Increased energy efficiency could result from changing the operating control strategies of the tool or system, from redesigning the tool or its support systems, or from replacing its components with more efficient alternatives.

The fact that these tools and systems are the largest energy consumers in the fab suggests, but does not necessarily mean, that the most valuable energy efficiency improvements can be gained from them. Chiller systems, for example, are frequently among the major energy consumers in any manufacturing facility. Chiller system suppliers may have already invested a significant amount of research and development into making these systems as energy efficient as possible, and it is possible that further efficiency gains may be small.[25] Process tools, on the other hand, are made by individual manufacturers to serve a variety of purposes. Gaining an across-the-board energy efficiency improvement among all process tools would require high levels of collaboration between tool manufacturers and fabs. This study may set the groundwork for such collaboration, but much work remains to be done in this area.

Baseline Values of Energy Consumption

Table 4-1 summarizes baseline energy consumption data expressed in kilowatt-hours per unit of production from the 14 participating fabs and shows the number of fabs that submitted data for each system; the minimum, maximum, and average consumption level reported for each system; and the standard deviation of the efficiency values reported.

The table also reports two calculated values that should be helpful in interpreting the overall results of this study. The first value is the standard deviation of the reported efficiency values divided by the average. This essentially normalizes the standard deviations so that they can be compared directly with one another. Lower values in this column, such as 0.039 for the chillers/central plant and 0.251 for the total fab, indicate that the submitted data for these systems were more consistent than for other systems with higher values of standard deviation divided by the average, such as 1.248 for the makeup air systems.

The second value is the minimum value plus the average value divided by two—alternatively, the midpoint between the minimum and average reported efficiency values. In cases where the distribution of the efficiency values is essentially flat, approximately 25% of fabs that participated in this study would have performed at this level of efficiency or better. This value is provided as an estimate of a potentially achievable energy consumption level for fabs given the limitations of data reliability and accuracy encountered in this study.

[25] In reality, improvements in efficiency and use of chiller plants can have a significant impact on overall fab energy use.

Table 4-1
Baseline Metrics for the 14 Surveyed Fabs

Metric	n[a]	kWh/unit of production			St Dev	St Dev/ Avg[b]	(Min+Avg)2[c]	Most Efficient Fabs		
		Min	Max	Avg				1	2	3
Facilities systems										
Chillers/central plant	14	0.054	0.163	0.100	0.033	0.329	0.077	14	12	13
Makeup air system fans	14	0.003	0.062	0.013	0.016	1.248	0.008	4	10	2
Recirculating air system fans	14	0.011	0.139	0.046	0.035	0.752	0.029	8	4	2
Exhaust air system fans	14	0.006	0.051	0.015	0.011	0.768	0.010	9	2	10
Nitrogen plant	12	0.005	0.067	0.031	0.018	0.581	0.018	2	7	3
Compressed dry air system	10	0.007	0.018	0.011	0.004	0.321	0.009	5	1	4
Process cooling water pumping system	14	0.001	0.009	0.005	0.003	0.533	0.003	9	14	12
Ultrapure water system	14	0.003	0.036	0.017	0.010	0.581	0.010	2	10	1
Process tools (tool production index)	14	0.062	0.257	0.137	0.050	0.368	0.099	9	10	1
Total fab (electrical utilization index)[d]	14	0.286	0.637	0.393	0.099	0.251	0.340	2	14	7

Metric	n[a]	kWh/in^2			St Dev	St Dev/ Avg[b]	(Min+Avg)/2[c]	Most Efficient Fabs		
		Min	Max	Avg				1	2	3
Total fab (production efficiency index)	13	5.364	10.229	7.449	1.596	0.214	6.407	9	2	4

[a] Number of fabs reporting data on these systems.

[b] This column normalizes the standard deviations so they are comparable to one another. A higher value indicates more variation in the underlying data.

[c] The values in this column represent the midpoint between the minimum and average values of kWh per unit of production. This value is an estimate of the potentially achievable energy consumption level for fabs given the limitations of data reliability and accuracy encountered in this study. This approach was adopted to reduce the possibility that the target values are due to inaccurate data instead of improved efficiency or reduced use. The extent to which this energy consumption level can be applied to other fabs outside the study group is unknown.

[d] Total fab electricity usage was reported separately, not calculated as a sum of reported facility and tool energy use.

The table also indicates the three most efficient fabs for each facility area. Finally, the more familiar metric of total fab kWh/inch^2 (kWh/millimeter^2) of wafer processed is provided for comparison.

Multiplying the average total fab electrical utilization index by an assumed cost of electricity of U.S.$0.05 per kWh, the baseline data reveals that the average overall cost of electricity for an operating a fab is approximately U.S.$0.0197 per unit of production, U.S.$0.3725 per square inch of wafer processed, or U.S.$18.71 for a typical 8-inch wafer. The total annual cost of energy for an average fab in this study, with annual production at 299 million units of production, would therefore be approximately U.S.$5.89 million.

The baseline consumption levels reported in Table 4-1 may also be of value in the design of new fab facilities. Setting achievable industry-wide energy efficiency levels above the average level may challenge design teams to provide the highest level of performance possible.

Top Performing Fabs

Only fab 2 was among the top three performers in three of the five performance indices shown: it was the top performer in production index and electrical utilization index and the second highest performer in the production efficiency index. Fab 2 also was among the top performers in nearly every fab system studied in this report. It is an Asian fab located in one of the warmest climates of all the fabs studied. At just 3 years old, it is one of the newest fabs in the study, is rated at class 100–1,000, and was designed with minienvironments. This fab also has the highest production level of any fab in the study.

Four fabs were among the top three performers in two of the five performance indices shown. These were fabs 4, 5, 9, and 10. Fabs 4 and 5 are 3 years old and are in Asia. Fabs 9 and 10 are in the United States. Fab 10 is also only 3 years old, but fab 9, at 14 years old, is one of the oldest fabs in the study. It is also one of the few fabs studied that uses 150 mm wafers in its production process.

Four additional fabs were among the top three performers in one of the five performance indices. These were fabs 1, 7, 12, and 14.

Top performing fabs tended to be newer fabs, minienvironment fabs, and fabs that had undertaken affirmative measures to minimize exfiltration. Top performing facilities systems also tended to be those that were equipped with high efficiency motors and variable speed fans and drives.

Conclusions About Energy Use in Process Areas and by Process Area Tools

By measuring electricity loads and process cooling water, UPW, and exhaust flows among tools in six key process areas, the project team was able to make conclusions about energy use in process areas and about design specifications of tool support systems and, to a lesser extent, process area tools. The six key process areas studied were patterning, thermal, thin films, ion implant, dry etch, and wafer cleaning. These process areas were previously identified as the highest energy-consuming process areas in fabs.

Process Areas

The study team identified the process areas with the highest electricity loads and process cooling water, UPW, and exhaust flow rates. The three process areas that consumed the most electricity were dry etch, thermal, and thin films. The three process areas that used the most process cooling water were dry etch, thin films, and wafer cleaning. The three process areas that used the most UPW were wafer cleaning, CMP, and patterning. The three process areas with the greatest exhaust flows were dry etch, wafer cleaning, and metrology. These results are summarized in Table 4-2.

Table 4-2
Load and Flow Allocations by Process Area

Process Area	Load or Flow			
	Electricity	Process cooling water	Ultrapure water	Exhaust
Patterning	15.1%	8.9%	8.9%	11.1%
Thermal	17.5%	11.7%	0.8%	8.6%
Thin films	24.3%	34.5%	0.2%	13.3%
Dry etch	22.0%	22.5%	0.1%	39.8%
Ion implant	9.6%	10.0%	-	5.0%
Wafer cleans	7.7%	11.4%	79.9%	14.8%
Other	3.8%	1.0%	10.1%	7.4%

Data in the table show how each load and flow is allocated on a normalized basis among key process areas. Data were derived from measurements of loads and flows in individual tools, which were then aggregated by process area.

Process Area Tools and Their Support Systems

Despite the large volume of tool measurement data collected, not enough measurements were taken of any single tool to make robust conclusions or recommendations on any particular make and model. However, by aggregating the tool data by process area, observations and conclusions were made on aggregated tool sets.

The participating fabs collected data on measured loads and flow rates in operating tools and on the load and flow rate design specifications for tools provided by the tool manufacturers. Planergy then compared the measured and designed load and flow rates to see whether tools actually used the amount of electricity, process cooling water, UPW, and exhaust they were designed to handle.

The median designed-to-measured load and flow ratios for each process area are summarized in Table 4-3. The median tool electricity usage tended to be lower than the manufacturers' design specifications in all key process areas (patterning, thermal, thin films, dry etch, ion implant, and wafer cleaning). The median tool process cooling water usage was lower than design specifications in all but the wafer cleaning process area, in which it was equal to design specifications. The median tool UPW usage was lower than design specifications in the dry etch and wafer cleaning process areas.[26] The median tool exhaust flows were lower than design specifications in the thin films and dry etch process areas.

Table 4-3
Median Designed-to-Measured Ratios by Process Area

Process Area	Load or Flow			
	Electricity	Process cooling water	Ultrapure water	Exhaust
Patterning	2.7	1.7	—	0.9
Thermal	5.0	2.4	—	0.8
Thin films	3.8	1.2	0.9	1.2
Dry etch	4.6	1.5	1.6	1.4
Ion implant	2.7	1.2	1.6	1.0
Wafer cleans	4.8	1.1	1.9	0.9

Combining the data from Table 4-2 and Table 4-3, it may be possible to identify tool sets that are relatively large consumers of electricity, process cooling water, UPW, and exhaust, but present opportunities for collaboration with equipment suppliers to improve design specifications.

[26] However, strong conclusions about ultrapure water support system and tool overdesign are not warranted because half of the dry etch tools were actually underdesigned for ultrapure water use, even though the median value showed evidence of overdesign.

Through this analysis, the dry etch process area tools and their support systems appear to be candidates for reduced design in electricity loads and process cooling water and exhaust flows. The thermal process area tools and their support systems appear to be candidates for reduced design in electricity loads and process cooling water flows. The thin films process area tools and their support systems appear to be candidates for reduced design in exhaust flows. Finally, the wafer cleaning process area tools and their support systems appear to be candidates for reduced design in UPW use.

Conclusions About Reported Energy Conservation Measures

Among the six fabs that reported energy conservation measures, the total value of the estimated annual savings derived from these measures was U.S.$11.1 million, or U.S.$1.8 million on average per fab. Five of the six fabs that reported energy conservation measures were 5 years old or less. These results demonstrate that cost-effective energy conservation measures can be found even in relatively new facilities.

Conclusions About Reported Best Practices

Participating fabs were asked to submit best energy management practices to share with other fabs. The most frequently reported best practices related to the following:

- Major facilities systems and subsystems
- Installation of measurement, control, and monitoring systems
- Incorporation of energy efficiency into overall facility design and engineering record keeping activities
- Use of energy efficient motors

The reported best practices are consistent with other findings presented in this report. For example, the data collected indicated that chillers, makeup air fans, and recirculating air fans together constitute about half of the energy use in the fabs studied, and participating companies reported a large number of best practices that related directly to the operation of these major systems. Four out of the five fabs that submitted best practices specifically referenced the chillers and air systems.

Three of the five fabs submitted best practices relating to installing and using sophisticated measurement, control, and monitoring systems within the fab.

A surprise finding was the high number of design and record keeping procedures submitted as best practices. This category of best practices included internal procedures such as keeping design and engineering drawings on hand as a reference for facilities personnel as well as carefully documenting procedures for analyzing energy use within the fab.

Conclusions About the Study Methodology

This report represents a landmark study. There have been few or no wall-to-wall energy studies of fabs and no published uniform fab survey studies in the United States, Asia, or Europe. This project's development of standard terminology and methodologies for conducting energy studies in fabs represents a first step toward enabling future analyses of fab energy performance to be made:

- The standard terminology and metrics glossary represents consensus on terms, their definitions, and energy consumption metrics for facilities, subsystems, and process tool areas. It is a "lowest common denominator" framework developed in cooperation with 14 of the top 20 semiconductor manufacturers worldwide.
- The development of the *Guidance Document*, a standard procedure for collecting and reporting data, enabled more fabs to participate and report better quality data. Without the *Guidance Document*, individual fabs may have deemed the study untimely or too expensive to participate. The *Guidance Document* is the first known standardized procedure for measuring facility systems and subsystems and process area energy consumption in fabs.
- Despite the existence of the *Guidance Document*, because fabs and data collection points vary and because the document was subject to individual interpretation, some of the data reported by fabs was considered suspect.
- The study team also learned lessons that may enhance future energy analyses in fabs:
- Weather, generally, may not be a significant factor in maintaining consistent operating conditions in fabs. Therefore the effect of weather was not controlled for in energy load analysis unless it affected fab loads by more than 10%.
- Units of production can be used to effectively normalize and compare energy consumption among fabs with varying age, class, and wafer production.
- A double reporting process consisting of both "top down" and "bottom up" measurement methodologies is necessary to evaluate the accuracy of both reported fab data and reported fab data. For example, the double reporting process revealed that individual cooling load data submitted by process area accounted for a median value of just 62% of the total central plant cooling output. The double reporting process alerted the project team to these discrepancies in the cooling load data.
- This project used the knowledge gained from the initial two pilot site surveys to create a baseline study of energy consumption in fabs. Although the sample size used for this project is not large enough for reliable statistical analysis, the data is suitable for comparisons of facility energy use for screening purposes and for tracking energy improvements.

Other Conclusions

Weather can play a large role in the energy use of a fab, but the combination of the other fab systems can have a greater impact on fab operation than climate. Distribution of high and low values of total energy use per unit of production did not display any apparent correlation to climate.

In addition to weather, fab geometry, classification, and age were analyzed for their effect on energy consumption levels. Linear regressions did not show a strong correlation between these factors and fab energy use. This was due in part to the small sample size as well as to the lack of strong relationships in the data.

The cooling use data, provided by all the participants, could not always be accurately reconciled to the chiller plant output. This data set was therefore not suitable for further analysis and consequently omitted from other analyses.

This project demonstrated that it is possible to accurately measure loads and flow rates in operating tools without disrupting manufacturing operations. The participating fabs successfully made over 300 measurements of electrical loads and process cooling water, UPW, and exhaust flows in tools in six key process areas.

Recommendations of the Study Team

Recommendations for Fab Managers and Engineers

Fab managers and engineers are often confronted by pressure to comply with varying internal and external requirements. This study may be used by fab managers and engineers to provide better, more efficient, and more timely energy consumption analysis. It enables managers to

- Continuously improve internal performance indices through uniform energy consumption framework, including data standards, methodologies, and best practices.
- Identify baseline values to compare with fabs whose facility, subsystem, or process tool area characteristics closely resemble their own.
- Integrate energy consumption analysis requirements with other management functions to help achieve environmental and cost goals.
- Work with industry and government to ensure that energy and environmental compliance reflects global requirements and is thus cost-effective.

Most important to managers with demanding, multi-national business requirements, this study provides a framework for uniform collection and analysis of fab energy consumption data. This means that managers can use widely accepted data collection methodology, procedures and assumptions to continuously and appropriately measure and improve energy consumption. The procedures can be found in the *Guidance Document*.

Identify Baseline Energy Consumption Values for Facilities Systems and Process Areas

To achieve both economic and environmental goals, managers should consider using study data to evaluate the energy consumption of facilities systems and process areas.

This type of evaluation can help managers obtain the capital and buy-in necessary to identify improvement areas and implement concrete energy conservation measures. Managers can use baseline data together with the study framework to more effectively work with external customers and suppliers as well as with internal customers, such as operations, quality, finance and safety, that comply with ESH standard procedures.

When conducting such an evaluation, fab managers should keep in mind the following recommendations:

- The top performing facility systems or overall tool loads should be investigated to determine how they are achieving the higher efficiency.
- If a facility is high in a certain metric compared with the baseline value, it is prudent for the company to review its system operation to determine whether energy savings are cost-effective and obtainable through system modification or control optimization.
- Review of operations at facilities more efficient than the baseline values presented in this report will add understanding about how the higher efficiency levels are obtained.

Recommendations for the Semiconductor Industry

The requirement for repeatable, consistent products in international trade has driven the development and implementation of several types of environment, safety, and health standards.

- Further investigate the following relationships to better understand their effect on energy efficiency in the fab:
  - The effect of differential temperature settings on the efficiency of process cooling water systems
  - The effect of HEPA filter velocity, fab class, and exfiltration rates on the efficiency of recirculating, makeup, and exhaust air systems
  - The effect of outside air temperature on the operating efficiency of chiller systems
- Conduct follow-up studies to improve the efficiency of exhaust systems associated with semiconductor tools. Such studies could lead to design improvements as well as improved methodologies for balancing and rebalancing tools in operating fabs.
- Conduct follow-up studies to better understand the energy use requirements of the tools and tool categories identified in this study as being strong candidates for design improvements. These include dry etch, thermal, thin films, and wafer cleaning process area tools. Such studies would help tool suppliers improve utility consumption specifications.
- Use and refine this study’s framework for data collection and analysis in fabs to achieve water and energy use reduction goals.
- Ensure that de facto standards, as well as those that may become SEMI standards, reflect the conditions of the majority of global semiconductor manufacturers. This can reduce cost for suppliers as well, resulting in lower operating costs to manufacturers.
- Use this study’s framework for data collection and analysis in fabs together with commercial industry consensus to continuously track and monitor fab energy efficiency.

- Ensure that any future federal regulatory standards agree with internationally accepted procedures and metrics. This can significantly reduce costs from customers, peers and governments with conflicting audit and report requirements.
- The *National Technology Roadmap for Semiconductors* also identifies the following goals, which may be enabled by some of the lessons learned from this study:
- Decrease energy use. Increase efforts to research reduce energy reduction in process tools.
- Develop software design tools for cost, relative risk, and design tool effectiveness. Again, the development of the *Guidance Document* and the conclusions about data collection procedures, assumptions, and metrics may be useful in furthering design tool software.

Recommendations for Future Study

The primary limitations of data used in this study stem from two factors: 1) self-reporting of data, which posed special challenges in ensuring consistency of measurement points and procedures between diverse fabs and 2) small sample sizes of participating fabs and tools, which made robust statistical analysis of data a challenge.

Data collection by multiple teams always leaves open the question of how issues particular to each fab were handled to predict loads and flow rates and to allocate the consumption of loads and flows to different process areas or facilities systems.

- The *Guidance Document* prepared for this study represented a good first attempt to account for differences among fabs and standardize measurement points and procedures, but amendments and additions should be made to account for unexpected fab conditions and problems encountered by participating fabs while collecting data for this project.
- Alternatively, future studies of fab energy use could employ consistent, third-party survey teams to collect data. This would eliminate uncertainty among project consultants about how data were derived, how measurements were taken, and what points within fabs were measured.

The small sample size of both project participants and facility and tool measurements also limited the applicability of the conclusions drawn from this study. While the participation of 14 fabs shows strong early interest in energy efficiency studies, the sample size is too small to be truly representative of the international installed base of fabs in any statistical sense. For process area tools, typically only three tools of each make and model were measured. Although tool measurements were aggregated by process area and some general conclusions drawn about energy use by process area tools, no robust conclusions about individual makes and models of process tools could be made.

For both process tools and facilities systems and subsystems, statistical analysis proved to be unproductive, although separate quantitative and qualitative analyses strongly supported several findings and conclusions.

In summary, future studies of energy consumption in fabs would benefit from wider participation; future studies of tool loads and flow rates would benefit from inclusion of a larger set of installed tools of each make and model of interest.

Further study is also needed to determine if weather, fab geometry, classification, and age of the facility affect energy usage within fabs in a statistically significant sense.

A
FAB ENERGY SURVEY DATA FORMS

Two survey forms are presented in this appendix. The first form consists of nine pages, labeled Sheet 1 through Sheet 7 and Sheets 8a and 8b. These forms were used by the participating fabs to collect data on various facility systems and subsystems and on tools. The form was developed using Microsoft Excel and was distributed to all participating fabs along with the *Guidance Document*, which summarized acceptable methods for measuring energy flows in an operating fab.

The second form asked participating fabs to list the top 20% of tools in the fab in electrical demand, UPW demand, and exhaust flow. This form also was developed using Microsoft Excel and was distributed to the participating fabs. The data collected helped the project team identify the process tools that were major consumers of electricity, UPW, and exhaust flows in operating fabs.

General Facility Information Sheet - 1

1	Company Name		
2	Fab Name		
3	Company Code		
4	Wafer Size		inches
5	Production Start Date		
6	Age of Fab		
7	Last Wafer Size Retrofit		Year
8	Current Wafer Starts per month		
9	Wafer start capacity		
10	Minimum Geometry		microns
11	Total Number of Production Tools (minus inspection and mask making)		
12	Average Number of Mask Layers		
13	Plant Peak Electric Load		kW
14	Plant Average Electric Load		kW
15	Facility Power Factor		
16	Average Electric Rate		US$/kWh
17	Design Cooling Load (tons/ft^2)		m^2/ton, ft^2/ton
18	Fab Operating Hours per year		
19	Average Monthly Raw Water Use		Gallons or Liters
20	Raw Water Source Average Temp.		F/C

Fab Design Please attach a general description of the design of the Fab (Word 6.0 format)

Fab Cleanroom Class and area

	Units (Please indicate)	**Class 0.01**	**Class 1**	**Class 10**	**Class 100**	**Class 1000**
Production Cleanroom Area	Sq.ft. or Sq.M.					
Fab Support Cleanroom Area	Sq.ft. or Sq.M.					
Minienvironment Area	Sq.ft. or Sq.M.					
SubFab	Sq.ft. or Sq.M.					
Fab Support Noncleanroom Area	Sq.ft. or Sq.M.					

Do not include office, cafeteria, analytical labs, E sort./test, etc.

Central Plant Data Sheet - 2

	Units (Please indicate)	
Chillers		
Average Measured Electric Load	**kW**	
Average Cooling Output	**tons of refrigeration**	
Annual Operating Time	**hours**	
General Description	**Please Attach a General Written Description of this Cooling System***	
	*** See example in Pilot Site 1 report Section 5.2.1.1 (Word 6.0 format)**	
Absorption Chillers (if any)		
Average Measured Electric Load	**kW**	
Average Cooling Output	**tons of refrigeration**	
Average Chiller Input		
Coef. Of Performance		
Fuel Source Heat Energy	**BTU x 10^6 or kW**	
Annual Operating Time	**hours**	
Tower Cooling		
Average Measured Electric Load	**kW**	
Annual Operating Time	**hours**	
Average Cooling Output	**tons of refrigeration**	
Chilled Water System Auxiliaries (all pumps, and towers)		
Average Measured Electric Load	**kW**	
Annual Operating Time	**hours**	
Chiller Plant Building Systems (HVAC, Lighting)		
Measured Average Building Electric Load	**kW**	
Annual Building Cooling Load	**ton-hours of refrigeration**	
Annual Operating Time	**hours**	
Thermal Storage systems	**Units (Please indicate)**	
Hot water (HW) or chilled water (CHW) or Ice	**HW/CHW/ICE**	
Useful storage capacity	**BTUH x 10^6**	
Temperature Supply	**F/C**	
Temperature Return	**F/C**	
Heating Water System		
Type of System	**Hot Water, High Temp.HW or Steam**	
Measured Average Boiler Energy Input	**BTU x 10^6 or kW**	
Measured Average System Auxiliaries (pumps, fans)	**kW**	
Annual Operating Time	**hours**	
Average Boiler Operating Efficiency	**%**	
General Description	**Please Attach a General Written Description of the Heating Water System***	
	*** See example in Pilot Site 1 report Section 3.1.3 (Word 6.0 format)**	
Other Fuel Fired Chillers		
Average Cooling Output	**tons of refrigeration**	
Average Chiller Input	**BTU x 10^6**	
Coef. Of Performance		
Fuel Sources Heat Energy	**BTU x 10^6 or kW**	

Makeup Air System Data Sheet - 3

	Units (Please indicate)	
General Data		
Variable Flow	**Yes/No**	
General Description	**Please Attach a General Written Description of the Makeup Air System***	
	*** see example in pilot sites 1 & 2 Section 3.2.1 (Word 6.0 format)**	
Air Handling Unit Data		
Number of units		
Average measured electric load (all operating units)	**kW**	
Average Flow	**CFM or CMH**	
Discharge Temperature Setpoint (wet bulb)	**degrees F or C**	
Discharge Temperature Setpoint (dry bulb)	**degrees F or C**	
Annual Operating Time	**hours**	
Average Annual Cooling Load	**ton-hours of refrigeration**	

Reheat Energy Type

Gas Fired Boiler	______________________%
Diesel Fired Boiler	______________________%
Heat Recovery Chiller	______________________%
Chilled Water Return Coil	______________________%
Electric Boiler or Electric Coils	______________________%
Heat Pipe	______________________%
Run Around Heat Recovery Loop	______________________%

Recirculating Air System Data Sheet - 4

	Units (Please indicate)	
General Data		
Air Velocity 6 inches below HEPA Filters	**Ft./min. or m/min.**	
Fab Temperature Setpoint	**degrees F or C (+/-)**	
HEPA Coverage Area (within cleanroom)	**% of Total**	
Fab Humidity	**% Relative (+/-)**	
Fab Pressurization	**in. H2O or Pascals**	
General Description	**Please Attach a General Written Description of the Recirculating Air System***	
	*** See example in Pilot site 1 Section 3.3 (Word 6.0 format)**	
Air Handling Unit Data		
Number of FTU		
Number of FFU		
FTU average measured electric load (all units)	**kW**	
FFU average measured electric load (all units)	**kW**	
Average FTU Flow	**CFM or CMH**	
Average FFU Flow	**CFM or CMH**	
Discharge Temperature Setpoint	**degrees F or C**	
Annual Operating Time	**hours**	
Average Sensible Cooling Load	**tons of refrigeration or kW**	
Sensible Cooling Load	%	

Exhaust Air System Data Sheet - 5

	Units (Please indicate)	
General Exhaust System		
Variable Flow	**Yes/No**	
Number of Fan units		
Average measured electric load (all operating units)	**kW**	
Average Flow (all exhaust systems)	**CFM or CMH**	
Discharge Temperature	**degrees F or C**	
Annual Operating Time	**hours**	
General Description	**Please Attach a General Written Description of this Exhaust Air System***	
	*** See example in Pilot site 1 Section 6.1.4 (Word 6.0 format)**	
Scrubbed Exhaust System		
Variable Flow	**Yes/No**	
Number of Fan units		
Average measured electric load (all operating units)	**kW**	
Average Flow	**CFM or CMH**	
Discharge Temperature	**degrees F or C**	
Annual Operating Time	**hours**	
Solvent Exhaust System		
Variable Flow	**Yes/No**	
Number of Fan units		
Average measured electric load (all operating units)	**kW**	
Average Flow	**CFM or CMH**	
Discharge Temperature	**degrees F or C**	
Annual Operating Time	**hours**	
Acid Exhaust System		
Variable Flow	**Yes/No**	
Number of Fan units		
Average measured electric load (all operating units)	**kW**	
Average Flow	**CFM or CMH**	
Discharge Temperature	**degrees F or C**	
Annual Operating Time	**hours**	
Ammonia Exhaust System		
Variable Flow	**Yes/No**	
Number of Fan units		
Average measured electric load (all operating units)	**kW**	
Average Flow	**CFM or CMH**	
Discharge Temperature	**degrees F or C**	
Annual Operating Time	**hours**	

Support Systems Data Sheet - 6

	Units (Please indicate)	
Nitrogen Plant		
Average Measured Electric Load	**kW**	
Average Measured Flow rate	**SCFM**	
Annual Operating Time	**hours**	
Compressed Dry Air		
Average Measured Electric Load	**kW**	
Average Measured Flow rate	**SCFM**	
Annual Operating Time	**hours**	
Process Cooling Water		
Measured Avg. Pumping Electric Load	**kW**	
Average Measured Flow rate	**GPM or LPM**	
Supply Temperature	**degrees F or C**	
Return Temperature	**degrees F or C**	
Ultra-Pure Water		
Measured Average Process and Pumping Electric Lc	**kW**	
Average Measured Flow rate	**GPM or LPM**	
Average Measured Consumption	**GPM or LPM**	
Supply Temperature	**degrees F or C**	
Percentage UPW Recycled for non-fab process	**%**	
Percentage UPW Recovered for FAB process	**%**	
Annual Heating Load (if required)	**BTUH x 10^6 or kWh**	
Annual Cooling Load (if required)	**ton-hours of refrigeration**	
Hot DI Water System (At DI plant or tool heaters)		
Measured Average Pumping Electric Load	**kW**	
Average Flow	**GPM or LPM**	
Average Water Source Temperature	**degrees F or C**	
Average Measured Consumption	**GPM or LPM**	
Percentage Recovered	**%**	
Percentage Recycled	**%**	
Supply Temperature at point of use	**degrees F or C**	
Annual Heating Load (if required)	**BTU x 10^6 or kW**	
Heating Energy Source		
Gas Boiler	________________________%	
Diesel Boiler	________________________%	
Electric Boiler	________________________%	
Heat Recovery	________________________%	
Other	________________________%	
Process Vacuum		
Measured Average Electric Load	**kW**	
Fab Support		
Measured Average Electric Load	**kW**	
Annual Cooling Load	**ton-hours of refrigeration**	
Hours per year Cooling Required	**Hours**	
Lighting		
Fab Lighting Load	**kW**	
Annual Operating hours	**hours**	
Other Lighting Loads	**kW**	

Total Tool Load Data Sheet - 7

Electricity	**Units (Please indicate)**	
Measured Average Tool Load	**kW**	
Projected Annual Energy Use	**kWh**	
Total Minienvironment Fan Load	**kW (Measured/Estimated)**	

~~**Add tool energy use by type if available**~~

	Number of Tools	Electrical Average kW
Patterning (Tracks, Coat/Dev, Stepper)		
Thermal (Furnaces Horizontal/vertical, RTP, LPCVD includes HTO)		
Thin Films (CVD includes nitride, oxide, metals, silicides, PVD, EPI)		
Dry Etch (Plasma, High Density PE)		
Metrology (Microscopes, Inspection Equipment, Scanning Electron Microscopes)		
AMHS (Wafers, Reticles)		
CMP (CMP, Post CMP Clean, Backside Grinding, Slurry Treatment)		
Ion Implant		
Wafer Cleaning (All sinks used in wafer cleaning and liquid etching)		
Totals		

Total Exhaust CFM/CMH	PCW GPM/LPH	DI/UPW GPM/LPH

Individual Tool Load Data Sheet - 8a

	Units (Please indicate)	Tool 1	Tool 2
Tool Information			
Tool Name			
Process			
Tool Supplier			
Model			
Company Specific Tool Identifier (if different from name, i.e. CVD03)			
Electricity			
Average Measured Load	**kW**		
Design Load	**kW**		
Process Cooling Water			
Average Measured Flow	**GPM or lpm**		
Design Flow	**GPM or lpm**		
Supply Temperature	**degrees F or C**		
Return Temperature	**degrees F or C**		
Ultra-Pure Water			
Average Measured Consumption	**GPM or lpm**		
Design Usage	**GPM or lpm**		
General Exhaust			
Average Measured Flow	**CFM or CMH**		
Design Flow	**CFM or CMH**		
Scrubbed Exhaust			
Average Measured Flow	**CFM or CMH**		
Design Flow	**CFM or CMH**		
Solvent Exhaust			
Average Measured Flow	**CFM or CMH**		
Design Flow	**CFM or CMH**		
Acid Exhaust			
Average Measured Flow	**CFM or CMH**		
Design Flow	**CFM or CMH**		
Ammonia Exhaust			
Average Measured Flow	**CFM or CMH**		
Design Flow	**CFM or CMH**		

Tool 3	Tool 4	Tool 5	Tool 6	Tool 7

Individual Tool Load Data Sheet - 8b

	Units (Please indicate)	Tool 8	Tool 9	Tool 10
Tool Information				
Tool Name				
Process				
Tool Supplier				
Model				
Company Specific Tool Identifier (if different from name, i.e. CVD03)				
Electricity				
Average Measured Load	**kW**			
Design Load	**kW**			
Process Cooling Water				
Average Measured Flow	**GPM or lpm**			
Design Flow	**GPM or lpm**			
Supply Temperature	**degrees F or C**			
Return Temperature	**degrees F or C**			
Ultra-Pure Water				
Average Measured Consumption	**GPM or lpm**			
Design Usage	**GPM or lpm**			
General Exhaust				
Average Measured Flow	**CFM or CMH**			
Design Flow	**CFM or CMH**			
Scrubbed Exhaust				
Average Measured Flow	**CFM or CMH**			
Design Flow	**CFM or CMH**			
Solvent Exhaust				
Average Measured Flow	**CFM or CMH**			
Design Flow	**CFM or CMH**			
Acid Exhaust				
Average Measured Flow	**CFM or CMH**			
Design Flow	**CFM or CMH**			
Ammonia Exhaust				
Average Measured Flow	**CFM or CMH**			
Design Flow	**CFM or CMH**			

Tool 11	Tool 12	Tool 13	Tool 14

B

TOP PERFORMERS' BEST PRACTICES SURVEY DATA FORMS

This appendix presents the survey forms given to the three most efficient fabs (in terms of kWh/unit of production) in each facility system and tool category. There were nine such categories in this study:

- Chillers/central plant
- Makeup air system
- Recirculating air system
- Exhaust air system
- Nitrogen system
- Compressed dry air system
- Process cooling water system
- UPW system
- Process tools

The survey forms were designed to provide the project team with more detailed data about the top performing systems, and to gain insights from fab personnel as to why the system outperformed others in the study group. The results

CHILLER PLANT (PAGE 1 OF 6)

Who is filling out this section of the survey?

Name ________________________________ (required)

E-mail address ________________________________ (required)

Telephone number ________________________________ (required)

We will e-mail you to schedule a time for a follow up phone interview.

Your fab has been identified as one of the top performers in the category identified at the top of this page. This survey is intended to help us understand why your fab performed well relative to its peers.

Based on your knowledge of your fab and the other fabs participating in this study, why do you think your fab performed well in this area? Is it because your fab is newer than others? Designed more efficiently than others? Makes a product that requires less energy in this category than others? Uses innovative energy management procedures? Other ideas? Please elaborate.

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Please describe any significant performance upgrades you have made to this system in the past several years.

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For each upgrade, describe the resulting performance improvement.

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CHILLER PLANT (PAGE 2 OF 6)

Chillers and Chilled Water Supply

1. Please complete the table below. Each row pertains to a set of chillers in the fab. Start with the largest chillers.

Chiller Size (Tons)	Number of Chillers	Chiller Type	Design kW/ton	Process Areas Served
		❐ glycol ❐ chilled water ❐ heat recovery ❐ variable speed ❐ other____		❐ Patterning ❐ Thermal ❐ Thin Films ❐ Dry Etch ❐ Metrology ❐ CMP ❐ Ion Implant ❐ Wafer Cleaning ❐ Other ____
		❐ glycol ❐ chilled water ❐ heat recovery ❐ variable speed ❐ other____		❐ Patterning ❐ Thermal ❐ Thin Films ❐ Dry Etch ❐ Metrology ❐ CMP ❐ Ion Implant ❐ Wafer Cleaning ❐ Other ____
		❐ glycol ❐ chilled water ❐ heat recovery ❐ variable speed ❐ other____		❐ Patterning ❐ Thermal ❐ Thin Films ❐ Dry Etch ❐ Metrology ❐ CMP ❐ Ion Implant ❐ Wafer Cleaning ❐ Other ____
		❐ glycol ❐ chilled water ❐ heat recovery ❐ variable speed ❐ other____		❐ Patterning ❐ Thermal ❐ Thin Films ❐ Dry Etch ❐ Metrology ❐ CMP ❐ Ion Implant ❐ Wafer Cleaning ❐ Other ____

CHILLER PLANT (PAGE 3 OF 6)

Questions 2-4 apply to each chiller system. Photocopy as necessary to complete for each chiller system.

2. Primary piping loop
   a. What % of the total chiller system load is accounted for by the primary piping loop?____%
   b. What is the average supply temperature? ____°F or ____°C
   c. What is the average return temperature? ____°F or ____°C
   d. Does the primary piping loop use a constant or variable flow?
      ❒ Constant
      ❒ Variable
   e. What is the design Horsepower/Ton of pumps? ____Hp/ton
   f. What is the actual Horsepower/Ton of pumps? ____Hp/ton
   g. Do the pumps have variable frequency drives (VFDs) ?
      ❒ Yes
      ❒ No
   h. Are high efficiency motors used?
      ❒ Yes
      ❒ No

3. Secondary Loop
   a. What % of the total chiller system load is accounted for by the secondary piping loop?__%
   b. What is the average supply temperature? ____°F or ____°C
   c. What is the average return temperature? ____°F or ____°C
   d. Does the primary piping loop use a constant or variable flow?
      ❒ Constant
      ❒ Variable
   e. What is the design Horsepower/Ton of pumps? ____Hp/ton
   f. What is the actual Horsepower/Ton of pumps? ____Hp/ton
   g. Do the pumps have variable frequency drives (VFDs) ?
      ❒ Yes
      ❒ No
   h. Are high efficiency motors used?
      ❒ Yes
      ❒ No

CHILLER PLANT (PAGE 4 OF 6)

4. Tertiary Loop
   a. What % of the total chiller system load is accounted for by the tertiary piping loop?____%
   b. What is the average supply temperature? ____°F or ____°C
   c. What is the average return temperature? ____°F or ____°C
   d. Does the primary piping loop use a constant or variable flow?
   ❒ Constant
   ❒ Variable
   e. What is the design Horsepower/Ton of pumps? ____Hp/ton
   f. What is the actual Horsepower/Ton of pumps? ____Hp/ton
   g. Do the pumps have variable frequency drives (VFDs) ?
   ❒ Yes
   ❒ No
   h. Are high efficiency motors used?
   ❒ Yes
   ❒ No

5. For all chillers, is the chiller sequencing procedure manual or automatic?
   ❒ Manual
   ❒ Automatic, please describe____

6. Please provide a brief description (i.e., 1-2 sentences) of how chilled water distribution pumps are controlled
   ____

7. Are high-efficiency motors used to power chilled water distribution pumps?
   ❒ Yes
   ❒ No

8. Are high-efficiency motors used to power condenser pumps?
   ❒ Yes
   ❒ No

9. Are high-efficiency motors used system wide?
   ❒ Yes
   ❒ No

10. Do you use thermal energy storage in your chiller plant?
   ❒ Yes
   ❒ No

11. Do you use any other innovative cooling technologies?
   ❒ Yes
   ❒ No
   If yes, please describe____

CHILLER PLANT (PAGE 5 OF 6)

12. Is any form of cooling recovery used?
    - ❒ Yes, tower cooling
    - ❒ Yes, using chilled water return to reheat discharge air in makeup fan system
    - ❒ Yes, using chilled water return for preheating outdoor air makeup
    - ❒ Yes, other form of cooling recovery. Please describe________________________________
    - ❒ No

13. Is the makeup air unit discharge air temperature constant or controlled from fab space conditions?
    - ❒ Constant
    - ❒ Controlled from fab space conditions

14. Is the makeup air unit dew point constant or controlled from fab space conditions?
    - ❒ Constant
    - ❒ Controlled from fab space conditions

15. Are separate chiller systems dedicated to the recirculating air fan cooling coils?
    - ❒ Yes
    - ❒ No

16. Are separate chiller systems dedicated to the makeup air fan cooling coils?
    - ❒ Yes
    - ❒ No

17. Are separate chiller systems dedicated to process cooling water cooling?
    - ❒ Yes
    - ❒ No

18. Are separate chiller systems dedicated to photo dehumidification?
    - ❒ Yes
    - ❒ No

19. Is a separate makeup air system used for photo dehumidification?
    - ❒ Yes
    - ❒ No

20. Is a separate makeup air system used for chemical mechanical polishing (CMP) type areas?
    - ❒ Yes
    - ❒ No

21. Are the chillers and pumps located in conditioned space?
    - ❒ Yes
    - ❒ No

22. Please attach a schematic of the chiller piping system to this survey.

CHILLER PLANT (PAGE 6 OF 6)

Condenser Water System

1. What is the tower design approach temperature? ____°F or ____°C

2. What is the tower design efficiency? ______horsepower per ton of heat rejection

3. Please provide a brief description (i.e., 1-2 sentences) of how condenser pumps are controlled____

4. Is the tower sequencing procedure manual or automatic?
❒ Manual
❒ Automatic, please describe____

5. Are the towers used for free cooling (direct) applications?
❒ Yes
❒ No
If yes, please describe ____

6. Are variable frequency drives (VFDs) used on cooling tower fans?
❒ Yes
❒ No

7. Are high efficiency motors used in the condenser water distribution system?
❒ Yes
❒ No

8. Are high efficiency motors used to power condenser pumps?
❒ Yes
❒ No

9. Are high efficiency motors used to power cooling tower fans?
❒ Yes
❒ No

10. Please attach a schematic of the condenser water piping system (indicating temperatures) to this survey.

MAKEUP AIR FAN SYSTEMS (PAGE 1 OF 2)

Who is filling out this section of the survey?

Name ______________________________ (required)

E-mail address ______________________________ (required)

Telephone number ______________________________ (required)

We will e-mail you to schedule a time for a follow up phone interview.

Your fab has been identified as one of the top performers in the category identified at the top of this page. This survey is intended to help us understand why your fab performed well relative to its peers.

Based on your knowledge of your fab and the other fabs participating in this study, why do you think your fab performed well in this area? Is it because your fab is newer than others? Designed more efficiently than others? Makes a product that requires less energy in this category than others? Uses innovative energy management procedures? Other ideas? Please elaborate.

____

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____

Please describe any significant performance upgrades you have made to this system in the past several years.

____

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____

For each upgrade, describe the resulting performance improvement.

____

____

____

1. What is the volume of the pressurized portion of the fab? _____ ft^3 or _____m^3
2. What is the design air flow per fan? ____cfm or ____cmh
3. What is the actual air flow per fan? ____cfm or ____cmh
4. What is the design fan static pressure in the makeup air unit? _____in. H_2O
5. What is the actual fan static pressure in the makeup air unit? _____in. H_2O

MAKEUP AIR FAN SYSTEMS (PAGE 2 OF 2)

6. What is the fan design efficiency rating (from manufacturer's specifications)? ____

7. Do you have HEPA filters in the makeup air system?
   ❒ Yes
   ❒ No

If yes, what is the design pressure drop across the filter? ____ in. H_2O or ____ Pascals

8. After the air leaves the makeup air system, does it go directly to the recirculation fan system return or to a supply air plenum?
   ❒ Recirculation fan system
   ❒ Supply air plenum
   ❒ Other, please describe ____
   ____

9. Are high efficiency motors used in the makeup air system?
   ❒ Yes
   ❒ No

10. Are VFDs used in the makeup air system?
    ❒ Yes
    ❒ No

RECIRCULATING FAN SYSTEMS (PAGE 1 OF 2)

Who is filling out this section of the survey?

Name ________________________________ (required)

E-mail address ________________________________ (required)

Telephone number ________________________________ (required)

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____

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Please describe any significant performance upgrades you have made to this system in the past several years.

____

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For each upgrade, describe the resulting performance improvement.

____

____

____

1. What is the design flow rate ? ____cfm or ____ cmh

2. What is the actual flow rate ? ____ cfm or ____ cmh
   If they are different, how was the new flow rate selected?
   ____
   ____
   ____

RECIRCULATING FAN SYSTEMS (PAGE 2 OF 2)

3. What is the fan design efficiency rating (from manufacturer's specifications)? ____

4. What is the design static pressure in the recirculating air units?
 ____ in. H_2O or ____ Pascals.

5. What is the actual static pressure in the recirculating air units?
 ____in. H_2O or ____ Pascals

6. Do you use HEPAs, ULPAs, or both?
 ❒ HEPAs (High Efficiency Particulate Air filters)
 ❒ ULPAs (Ultra Low Particulate Air filters)
 ❒ Both HEPAs and ULPAs
 ❒ Other, please describe. ____

7. What is the basis for your filter changeout schedule?
 ❒ Time (we change them every ___ years)
 ❒ Filter loading (we check the loading every ____ years)
 ❒ Other basis, please describe.____
 ____

8. What is the pressure drop across the HEPAs, ULPAs, or other filter units?
 For HEPAs ____ in. H_2O or ____ Pascals
 For ULPAs ____ in. H_2O or ____ Pascals
 Other filters ____ in. H_2O or ____ Pascals

9. For HEPAs (if applicable): What is the filter design velocity? _____fpm or ____m/s
 What is the actual filter velocity? _____fpm or ____m/s

10. For ULPAs (if applicable): What is the filter design velocity? ____ fpm or ____ m/s
 What is the actual filter velocity? ____ fpm or ____ m/s

11. What is the type of fan volume control used?
 ❒ Econocone
 ❒ Discharge Dampers
 ❒ Inlet Guide Vanes
 ❒ Variable Speed Drive
 ❒ None
 ❒ Other, please describe ____
 ____

12. Age of HEPAs / ULPAs? HEPAs____ years ULPAs ____ years

13. Are high efficiency motors used?
 ❒ Yes
 ❒ No

14. Please attach a schematic of the recirculating fan system to this survey.

EXHAUST AIR SYSTEM (PAGE 1 OF 2)

Who is filling out this section of the survey?

Name ________________________________ (required)

E-mail address ________________________________ (required)

Telephone number ________________________________ (required)

We will e-mail you to schedule a time for a follow up phone interview.

Your fab has been identified as one of the top performers in the category identified at the top of this page. This survey is intended to help us understand why your fab performed well relative to its peers.

Based on your knowledge of your fab and the other fabs participating in this study, why do you think your fab performed well in this area? Is it because your fab is newer than others? Designed more efficiently than others? Makes product that requires less energy in this category than others? Uses innovative energy management procedures? Other ideas? Please elaborate.

____
____
____

Please describe any significant performance upgrades you have made to this system in the past several years.

____
____
____

For each upgrade, describe the resulting performance improvement.

____
____
____

1. What is the exhaust fan design efficiency rating (from manufacturer's specifications)? ____
2. What is the design static pressure in the exhaust air system? ____in. H_2O or ____Pascals
3. What is the actual static pressure in the exhaust air system? ____in. H_2O or ____Pascals
4. What is the design flow in the exhaust air system? ____ cfm or ____ cmh
5. What is the actual flow in the exhaust air system? ____ cfm or ____ cmh

EXHAUST AIR SYSTEM (PAGE 2 OF 2)

6. Identify the type of pollution control devices you use
   ❒ burn boxes
   ❒ scrubbers / air washers
   ❒ Other, please describe ____
   ____

7. Where does heat (thermal) exhaust from tools go?
   ❒ Return air
   ❒ Exhaust system
   ❒ Other, please describe. ____
   ____

8. How often do you rebalance the exhaust system?
   ❒ Upon installation of new tools
   ❒ Quarterly
   ❒ Annually
   ❒ Other, please describe ____
   ____

9. Is exhaust automatically controlled at the tool level in any tools?
   ❒ Yes
   ❒ No
   If yes, in what type(s) of tools is exhaust automatically controlled?
   ❒ Patterning
   ❒ Thermal
   ❒ Thin Films
   ❒ Dry etch
   ❒ Wafer clean
   ❒ Metrology
   ❒ Implant
   ❒ CMP
   ❒ Other ____

NITROGEN SYSTEMS (PAGE 1 OF 2)

Who is filling out this section of the survey?

Name ________________________________ (required)

E-mail address ________________________________ (required)

Telephone number ________________________________ (required)

We will e-mail you to schedule a time for a follow up phone interview.

Your fab has been identified as one of the top performers in the category identified at the top of this page. This survey is intended to help us understand why your fab performed well relative to its peers.

Based on your knowledge of your fab and the other fabs participating in this study, why do you think your fab performed well in this area? Is it because your fab is newer than others? Designed more efficiently than others? Makes product that requires less energy in this category than others? Uses innovative energy management procedures? Other ideas? Please elaborate.

____
____
____

Please describe any significant performance upgrades you have made to this system in the past several years.

____
____
____

For each upgrade, describe the resulting performance improvement.

____
____
____

1. Is the nitrogen system electrically metered separately from the remaining facility?
   ❒ Yes
   ❒ No

2. What is the design capacity of the nitrogen system? ____ scfm

3. What is the operating capacity of the nitrogen system? ____ scfm

NITROGEN SYSTEMS (PAGE 2 OF 2)

4. What is the cooling source for the nitrogen plant?
   ❒ Glycol
   ❒ Water chiller
   ❒ Other, please describe____
   ____

5. What is the temperature of the cooling source? ____ °F or ____ °C

6. Is the nitrogen system used for other uses than providing nitrogen to processes? ❒ Yes
   ❒ No
   If yes, approximately what % of the nitrogen system capacity is used for other processes?
   ____ %

7. What is the purity specification of the nitrogen manufactured? ____ ppm or ____ ppb

8. Who was the manufacturer of your nitrogen plant?
   ❒ Praxair
   ❒ BOC
   ❒ Air Products
   ❒ Other (please specify) ____________________

COMPRESSED DRY AIR PLANT (PAGE 1 OF 2)

Who is filling out this section of the survey?

Name ________________________________ (required)

E-mail address ________________________________ (required)

Telephone number ________________________________ (required)

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____
____
____

Please describe any significant performance upgrades you have made to this system in the past several years.

____
____
____

For each upgrade, describe the resulting performance improvement.

____
____
____

1. What type of dry air compressors do you use? (check all that apply)
   ❒ Centrifugal
   ❒ Screw
   ❒ Reciprocating
   ❒ Other, please specify. ____
   ____

2. What is the compressor design capacity? ____ kW

COMPRESSED DRY AIR PLANT (PAGE 2 OF 2)

3. What is the compressor design flow rate? ____ cfm

4. What is your dewpoint specification? ____°F or ____°C

5. Is the compressor control sequencing procedure manual or automatic?
   ❒ Manual
   ❒ Automatic, please describe _______________________________________

6. Please provide a brief description (i.e., 1-2 sentences) of how air compressors are controlled.
   ____
   ____

7. Total number of compressors. ____

8. Number of compressors that are typically operating at one time. ____

9. What type of dryers do you use in the compressed dry air plant?
   ❒ Dessicant
   ❒ Other, please describe ____
   ____

10. What is the design capacity of the operating dryers? ____ scfm or ____ scmh

11. What is the actual operating pressure provided by the air compressors at the plant? ____ psi

PROCESS COOLING WATER (PAGE 1 OF 2)

Who is filling out this section of the survey?

Name ________________________________ (required)

E-mail address ________________________________ (required)

Telephone number ________________________________ (required)

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____
____
____

Please describe any significant performance upgrades you have made to this system in the past several years.

____
____
____

For each upgrade, describe the resulting performance improvement.

____
____
____

1. What is the nameplate efficiency of the process cooling water distribution pumps? ____
2. What is the design differential pressure of the process cooling water distribution pumps? ____ psi at ____ gpm

PROCESS COOLING WATER (PAGE 2 OF 2)

3. Is process cooling water automatically controlled at the tool level in any tools?
   ❒ Yes
   ❒ No
   If yes, in what type(s) of tools is process cooling water automatically controlled?(check all that apply)
   ❒ Patterning
   ❒ Thermal
   ❒ Thin films
   ❒ Dry etch
   ❒ Metrology
   ❒ CMP
   ❒ Ion implant
   ❒ Wafer cleaning
   ❒ Other, please describe ____

4. What form of volume control is used on the process cooling water system ? (check all that apply)
   ❒ Variable speed drive (VSD)
   ❒ Pump throttling
   ❒ Trim impellers
   ❒ Pump staging
   ❒ None
   ❒ Other, describe ____

5. Please attach a piping schematic showing locations, size, actual kW, and flow rates of process cooling water system

6. What type of heat exchangers are you using?
   ❒ Plate
   ❒ Other, describe ____

ULTRAPURE WATER (PAGE 1 OF 3)

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Name ________________________________ (required)

E-mail address ________________________________ (required)

Telephone number ________________________________ (required)

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____
____
____

Please describe any significant performance upgrades you have made to this system in the past several years.

____
____
____

For each upgrade, describe the resulting performance improvement.

____
____
____

1. What type of ultrapure water system do you have?
   ❒ Reverse Osmosis (RO)
   ❒ Other, please describe ____
   ____

2. What % of total kW of the system is due to pumps ____%

ULTRAPURE WATER (PAGE 2 OF 3)

3. What are the 5 highest pressure pumps in the ultrapure water system?

Pressure (psi)	Horsepower	Control Method	What Process Areas Does the Pump Serve?
		❒ VSD ❒ Throttling ❒ Trim impellers ❒ Pump staging ❒ Other____	❒ Patterning ❒ Thermal ❒ Thin Films ❒ Dry Etch ❒ Metrology ❒ CMP ❒ Ion Implant ❒ Wafer Cleaning ❒ Other____
		❒ VSD ❒ Throttling ❒ Trim impellers ❒ Pump staging ❒ Other____	❒ Patterning ❒ Thermal ❒ Thin Films ❒ Dry Etch ❒ Metrology ❒ CMP ❒ Ion Implant ❒ Wafer Cleaning ❒ Other____
		❒ VSD ❒ Throttling ❒ Trim impellers ❒ Pump staging ❒ Other____	❒ Patterning ❒ Thermal ❒ Thin Films ❒ Dry Etch ❒ Metrology ❒ CMP ❒ Ion Implant ❒ Wafer Cleaning ❒ Other____
		❒ VSD ❒ Throttling ❒ Trim impellers ❒ Pump staging ❒ Other____	❒ Patterning ❒ Thermal ❒ Thin Films ❒ Dry Etch ❒ Metrology ❒ CMP ❒ Ion Implant ❒ Wafer Cleaning ❒ Other____
		❒ VSD ❒ Throttling ❒ Trim impellers ❒ Pump staging ❒ Other____	❒ Patterning ❒ Thermal ❒ Thin Films ❒ Dry Etch ❒ Metrology ❒ CMP ❒ Ion Implant ❒ Wafer Cleaning ❒ Other____

ULTRAPURE WATER (PAGE 3 OF 3)

4. What is the actual operation production of the ultrapure water system?
   ____ gpm or ____ lpm

5. What is the design production of the ultrapure water system?
   ____ gpm or ____ lpm

6. Briefly describe any measures that have been taken to reduce ultrapure water use in the fab.
   ____
   ____

7. What % reduction did each measure provide?
   ____
   ____

8. Do you have any chemical mechanical polishing (CMP) processes in the fab?
   ❒ Yes
   ❒ No

PROCESS TOOLS (PAGE 1 OF 3)

Who is filling out this section of the survey?

Name ________________________________ (required)

E-mail address ________________________________ (required)

Telephone number ________________________________ (required)

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Please describe any significant performance upgrades you have made to this system in the past several years.

For each upgrade, describe the resulting performance improvement.

1. How many tools are there in your fab? ____

2. Of all the tools reported in question 1 above, approximately how many are in use less than 50% of the time? ____

3. Of all the tools reported in question 1 above, approximately how many are in use less than 25% of the time? ____

PROCESS TOOLS (PAGE 2 OF 3)

4. Of all the tools reported in question 1 above, approximately how many are in use less than 10% of the time? ____

5. Is the operation of tools managed differently in standby mode with respect to:
   Process cooling water? ❒ Yes ❒ No
   Ultrapure water? ❒ Yes ❒ No
   Exhaust? ❒ Yes ❒ No
   Electricity? ❒ Yes ❒ No

6. In furnace tools, do you take steps to minimize or otherwise optimize the idle temperatures?
   ❒ Yes
   ❒ No
   If yes, is the idle temperature controlled automatically or manually?
   ❒ Automatically
   ❒ Manually

7. In tools with auxiliary vacuum pumps, are the vacuum pumps shut down or operated at reduced capacity when the tool is not in use?
   ❒ Yes, shut down
   ❒ Yes, operated at reduced capacity
   ❒ No, vacuum pumps continue to run at full speed
   If yes, is the shutdown or reduced capacity controlled automatically or manually?
   ❒ Automatically
   ❒ Manually

8. In tools with auxiliary chillers (such as Neslab or Affinity chillers), are multiple tools served by single chillers
   ❒ Yes
   ❒ No

9. In tools with auxiliary chillers, is the shutdown of chillers controlled automatically or manually?
   ❒ Automatically
   ❒ Manually

PROCESS TOOLS (PAGE 3 OF 3)

10. Does the fab heat deionized (DI) or ultrapure water (UPW)?
    ❒ Yes
    ❒ No
    If yes, is the heat source:
    ❒ Electric
    ❒ Gas
    ❒ Other, please describe ____
    ____
    What is the heating provided for?
    ❒ At the tool
    ❒ Central plant
    ❒ Other, please describe ____
    ____

C
TOOL MEASUREMENT ASSIGNMENTS

This appendix summarizes the tool measurement assignments given to project participants by International SEMATECH. Thirteen of the 14 participating fabs submitted tool measurements for use in this study. The goal was to obtain at least three measurements of each tool type in each process area. The table lists tools by supplier and model name, and shows which fabs were assigned to make which measurements. Separate measurements were made of the same tool when it was used in different process areas, such as thin films or ion implant.

SUPPLIER	*MODEL*	*PROCESS*	ELECT. (WATTS)	1	2	3	4	5	6	7	8	9	10	11	12	13
APPLIED MATERIALS	CENTURA 5200	***THIN FILMS***	216,000.0		x											
	5200		52,000.0			x										
	CENTURA		145,000				x									
	CENTURA		122,000.0								x					
	CENTURA		127,000	x												
APPLIED MATERIALS	ENDURA	***THIN FILMS***	206,000.0					x								
	ENDURA		187,000.0		x											
	ENDURA		183,000.0								x					
	ENDURA		190,000.0	x												
APPLIED MATERIALS	ENDURA	***THIN FILMS***	108,000.0			x										
	ENDURA		108,000.0						x							
	5500 HP		178,000.0				x									
EATON	GSD 160	***ION IMPLANT***	122,400.0								x					
	NV GSD 160		60,000.0			x										
	NV-160		45,700.0						x							
EATON	GSD 200	***ION IMPLANT***	35,000.0						x							
	GSD 200		112,500.0												x	
	GSD 200HE		186,000.0				x									
EATON	GSD HE	***ION IMPLANT***	187,000.0												x	
	NV-GSD		24,000.0											x		
NOVELLUS	SPEED C-II	***THIN FILMS***	177,300.0				x									
	CONCEPT II		?		x											
	CONCEPT II		?													x
	C-II		129,000.0												x	
TEL	8500	***DRY ETCH***	147,000.0								x					
	8500		58,400.0							x						
	TE 8500		60,000.0					x								
TEL	UNITY 85 DP	***DRY ETCH***	89,000.0				x									
	UNITY 65D		120,000.0			x										
	WS-05		84,600.0			x										
LAM Research	TCP 9400	***DRY ETCH***	135,000.0				x									
	9400		64,800.0												x	
	9400		77,300.0					x								
LAM Research	ALLIANCE	***DRY ETCH***	140,000.0		x											
	TCP 9600		134,000.0				x									x
	9600		50,400.0							x						
	4428/9608		52,000.0	x												
LAM Research	RAINBOW 4520	***DRY ETCH***	?													x
	4528/4500		64,800.0												x	
	4528/4500		cfm											x		
	ALLIANCE 9400		145,500.0			x										
APPLIED MATERIALS	P 5000	***THIN FILMS***	144,000.0								x					
	P 5000		142,000.0					x								
	P 5000		81,000.0		x											
	P 5000		76,000.0	x												
APPLIED MATERIALS	P 5000	***THIN FILMS***	65,000.0							x						
	5000		36,400.0						x							
	5000		64,800.0												x	
TEL	ALPHA 8-S	***THERMAL***	141,000.0								x					
	ALPHA 8-S		?													x
	FTP		63,000.0							x						

SUPPLIER	*MODEL*	*PROCESS*	ELECT. (WATTS)	1	2	3	4	5	6	7	8	9	10	11	12	13
APPLIED MATERIALS	P 5200	***DRY ETCH***	103,000.0					x								
	P 5200		137,000.0					x								
	P 5200 MXP		134,000.0				x									
APPLIED MATERIALS	CENTURA	***DRY ETCH***	134,000.0				x									
	CENTURA		145,000.0			x										
	CENTURA		140,000.0		x											
APPLIED MATERIALS	8330/8310	***DRY ETCH***	?													x
	5300		97,200.0												x	
	CENTURA		128,000.0								x					
SANKYO	SWH	***WAFER CLEAN***	110,000.0								x					
DNS	820C		216,000.0		x											
KAIJO/SUGAI	S. ORDER		86,000.0					x								
APPLIED MATERIALS	PI 9500	***ION IMPLANT***	152,000.0					x								
	PRECISION 9500		?													x
	9500		65,500.0						x							
	9500XR80				x											
TEL	UW8000	***WAFER CLEAN***	71,100.0				x									
TEL	WS-07		67,000.0			x										
FSI	MERCURY		59,400.0							x						
VARIAN	E 500	***ION IMPLANT***	106,000.0				x									
	E 500HP		77,000.0					x								
	E 500		100,000.0	x												
	E 200	***ION IMPLANT***	60,000.0							x						
	E 220HP		?													x
	E 220HP		68,400.0												x	
THERMCO	?	***THERMAL***	86,000.0						x							
TEL	HORIZONTAL		?													x
TEL	IW6		40,000.0			x										
TEL	?		34,000.0	x												
SVG THERMCO	?		52,000.0	x												
APPLIED MATERIALS	CENTURA	***THERMAL***	166,000.0						x							
KOYO LINDBERG	VF 5100B		66,700.0			x										
GASONICS	HIPOX		57,600.0						x							
SVG	THERMCO HORIZONTAL	***THERMAL***	?													x
BTI	APOGEE		13,500.0											x		
MRC	ECLIPSE	***THIN FILMS***	83,200.0						x							
ANELVA	ILC-1060		127,000.0			x										
APPLIED MATERIALS	P5500		116,000.0							x						
QUESTER TECH	APT 5850		35,000.0											x		
TEL	MK-7	***PATTERNING***	136,800.0							x						
	MK-7		51,500.0					x								
	MK-8		cfm		x											
	MK-8		51,200.0							x						
CANON	2500I3	***PATTERNING***	21,000.0											x		
CANON	I2		35,200.0							x						
ASML	PAS 5500		?													x
ASML	/100		20,000.0	x												
HITACHI	M318 SX	***DRY ETCH***	68,700.0					x								
PSC	DES 220-456		51,500.0					x								
PSC	DES 312-304		78,000.0			x										
APPLIED MATERIALS	OMEGA	***DRY ETCH***	110,000.0		x											
MATTSON	ASPEN		122,400.0								x					

SUPPLIER	MODEL	PROCESS	EXHAUST (cfm)	1	2	3	4	5	6	7	8	9	10	11	12	13
SANKYO	SWL	***WAFER CLEAN***	5,970.0								x					
SUGAI	PEGASUS		3,369.0				x									
TEL	WS-7		3,006.0			x										
SCP	AUTOHOOD	***WAFER CLEAN***	3,000.0						x							
SMS	GAMMA		2,293.0							x						
SANKYO	SWH		4,300.0								x					
SMS	?		2,600.0	x												
TOHO	CUSTOM	***WAFER CLEAN***	2,117.0							x						
DNS	820C		1,800.0		x											
STEAG	WET BENCH		2,250.0												x	
KAIJO	S. ORDER	***WAFER CLEAN***	36,000 (elect.)					x								
FSI	SATURN MP		?													x
FSI	EXCALIBUR		1,757.0		x											
SCP	SCP 9200		?													x
TEL	UW 8000		2,268.0				x									
FSI	Mercury		670.0	x												
WATKINS JOHNSON	WJ 998	***THIN FILMS***	?													x
	WJ 999R		1,235.0											x		
	WJ 1000		2,174.0				x									
WATKINS JOHNSON	WJ 999	***THIN FILMS***	1,235.0							x						
	WJ 1000		1,650.0		x											
SCP	SCP 6800	***WAFER CLEAN***	?													x
SMS	WET BENCH		60											x		
DNS	WSW 821		48.3							x						
TEL	S. ORDER	***WAFER CLEAN***	39.6					x								
DNS	F-SINK SC		38.3			x										
KAIJO	?		26.4		x											
SMS	HOOD	***WAFER CLEAN***	50						x							
FSI			13												x	
	TOTALS:				***14***	***14***	***14***	***14***	***11***	***14***	***11***			***7***	***10***	***14***

D

DESIGNED-TO-MEASURED LOADS AND FLOW RATES BY PROCESS AREA

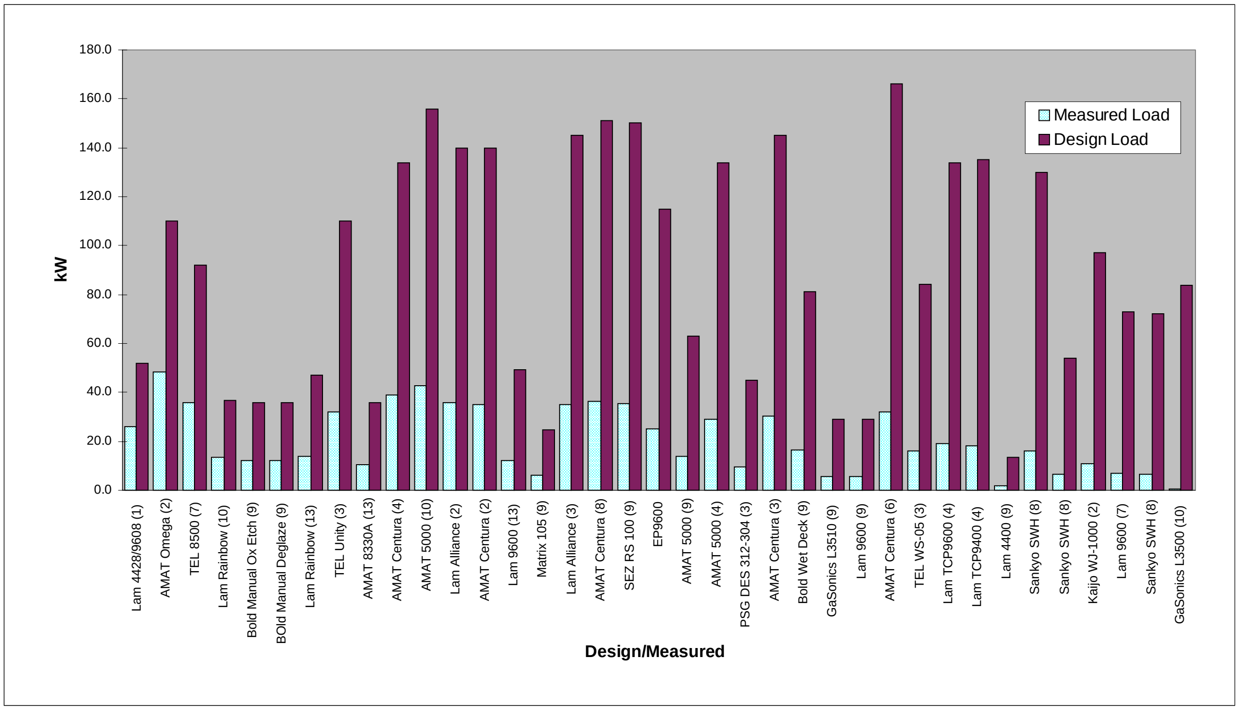
The following charts show the designed and measured loads and flows in tools organized by process area. These loads and flows include electricity loads, and process cooling water, ultrapure water, and exhaust flow rates.

Each chart presents two bars for each tool measured. The measured value bar indicates the load or flow as measured in an operating fab. The designed value bar indicates the tool manufacturer's designed load or flow specifications.

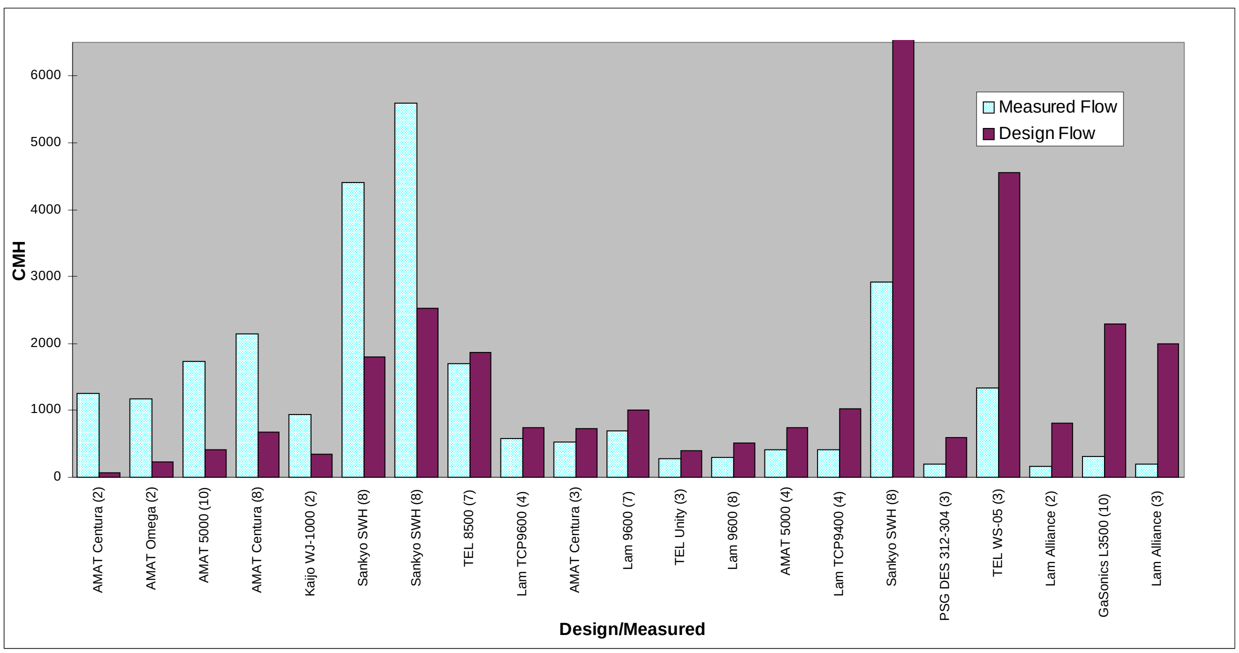
The data are presented in each chart with the designed-to-measured ratios decreasing from left to right. In other words, the tools on the left side of each chart have design usage rates that are higher than the loads or flows that were actually measured in the participating fabs. This could indicate the existence of an opportunity to reduce tool installation and support capital costs or, possibly, to improve the energy efficiency of the tool through appropriate design changes.

However, this conclusion should be drawn cautiously for four main reasons. First, a limited number of tool measurements were made by the project participants. For any particular make and model of a tool, the project team did not collect enough data to draw firm conclusions that would apply to all tools of that make and model. Second, there may be errors or inconsistencies in load or flow measurements because data were self-reported. The project team attempted to mitigate these errors by supplying participating fabs with a *Guidance Document* specifying acceptable methods of measurement, but it is unknown how closely those procedures were followed in every fab. Third, separate measurements of the same tool at different fabs or in different process areas yielded widely varying designed-to-measured ratios. This finding suggests that individual tools are used to perform a variety of functions within and among different process areas in the fab. While a tool may appear to be overdesigned for one function, it may actually be operating at design conditions for another. Fourth, variations in the physical specifications of each tool model may be present within or among fabs.

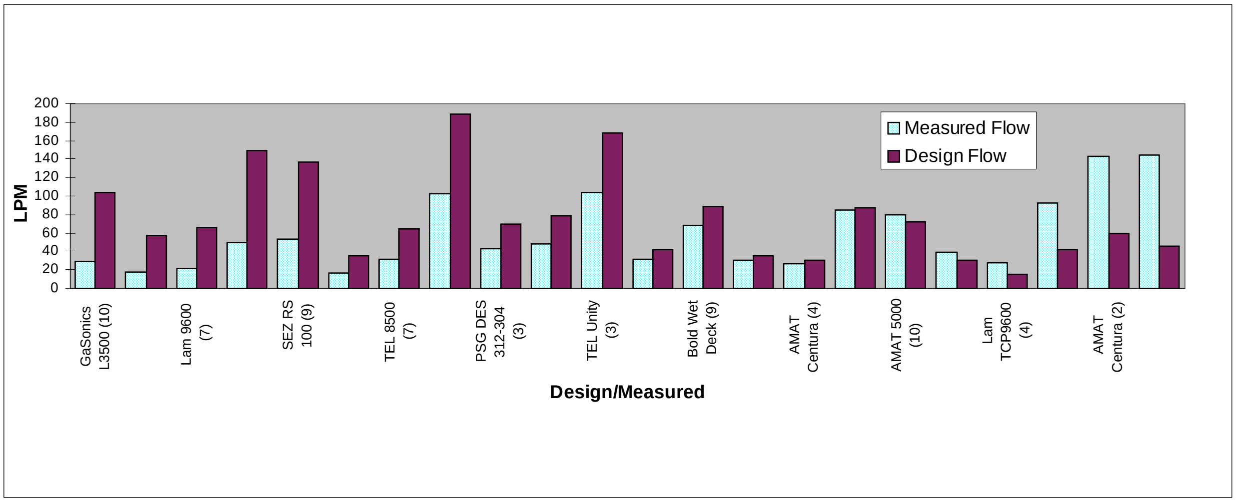
Because of these limitations, the project team was unable to make firm conclusions about the potential impact that could result from changes to the design parameters of any particular make and model of tool. However, by aggregating the tool data by process area, the study team was able to make some general and specific findings about the potential for reducing design values of fab tool support systems and tools to achieve energy and cost savings. These findings are discussed in the section titled Energy Use by Process Area.



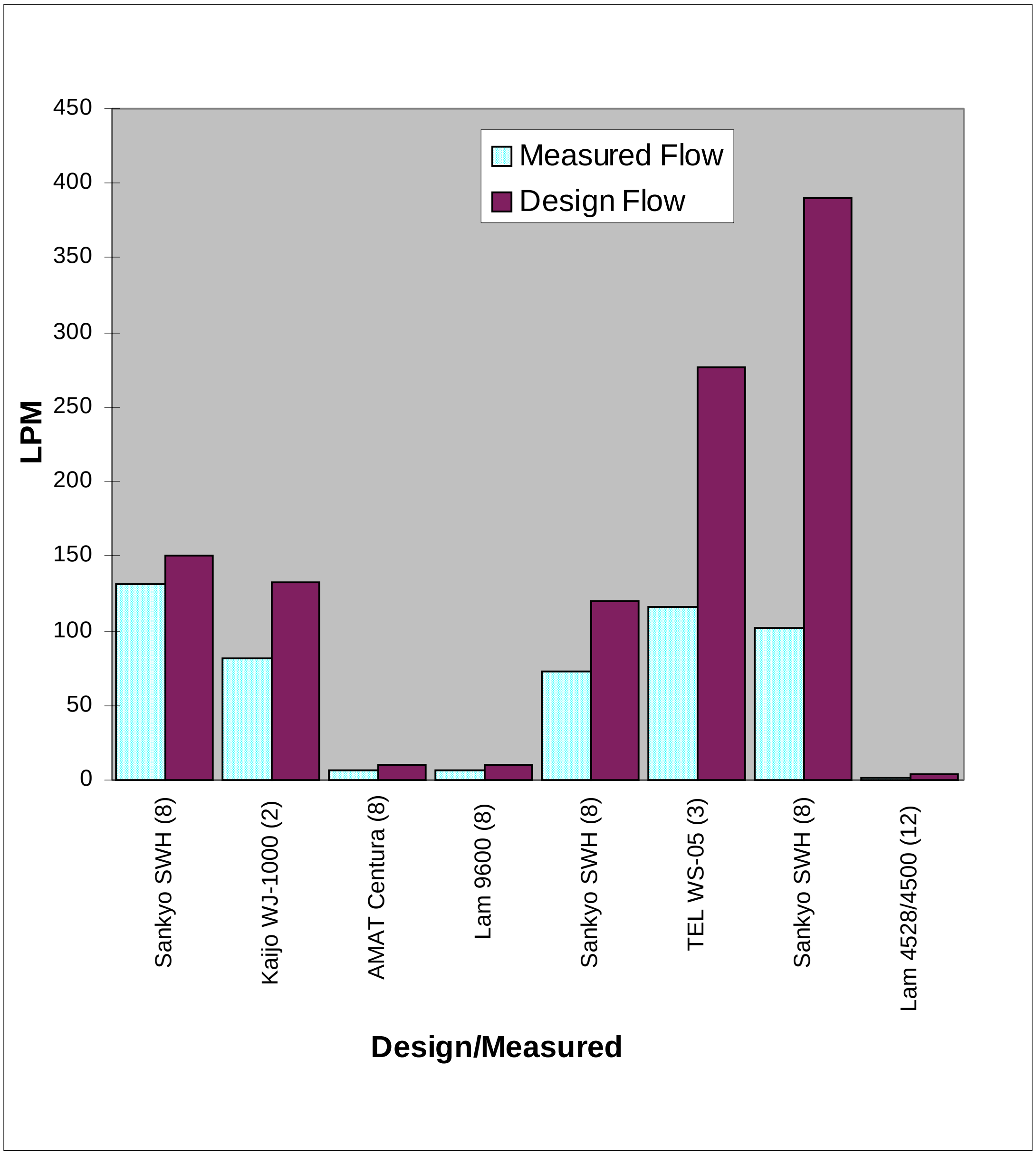
Dry Etch Process Area-Electricity



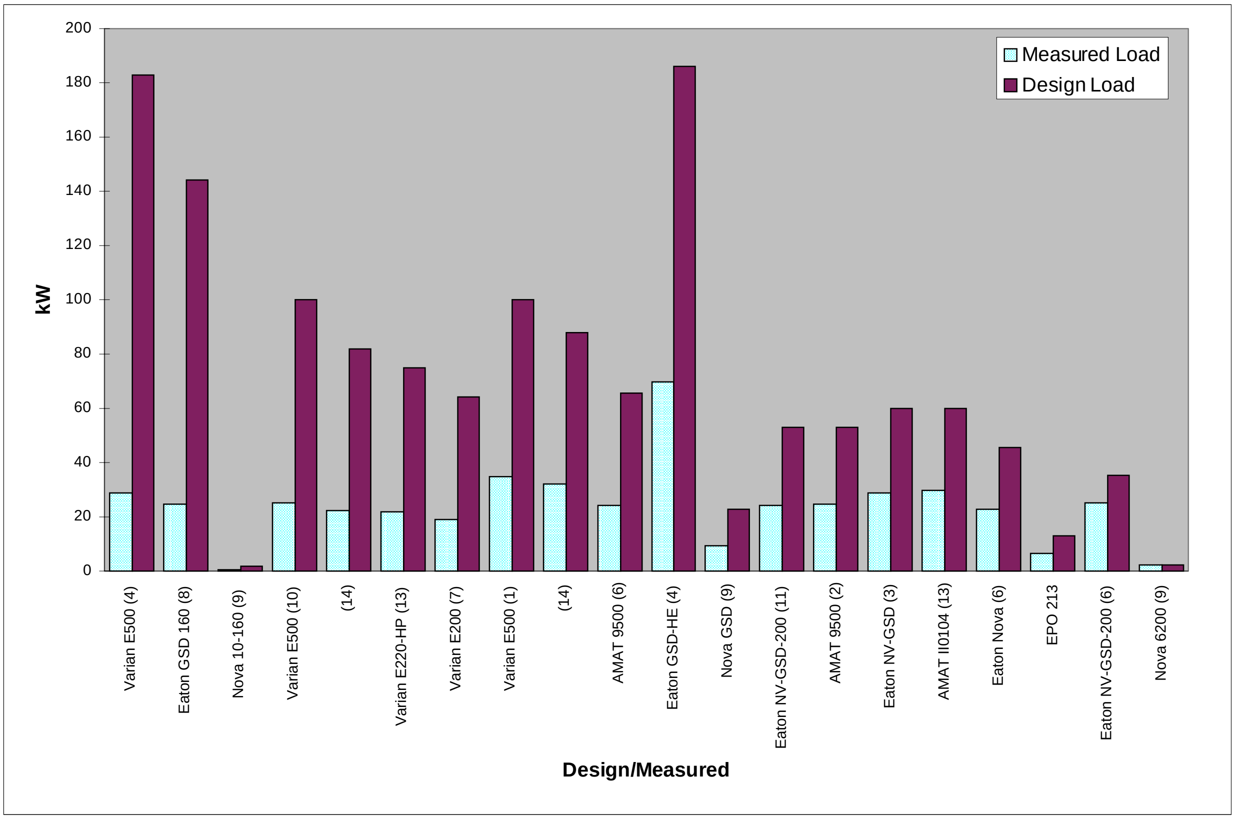
Dry Etch Process Area-Exhaust



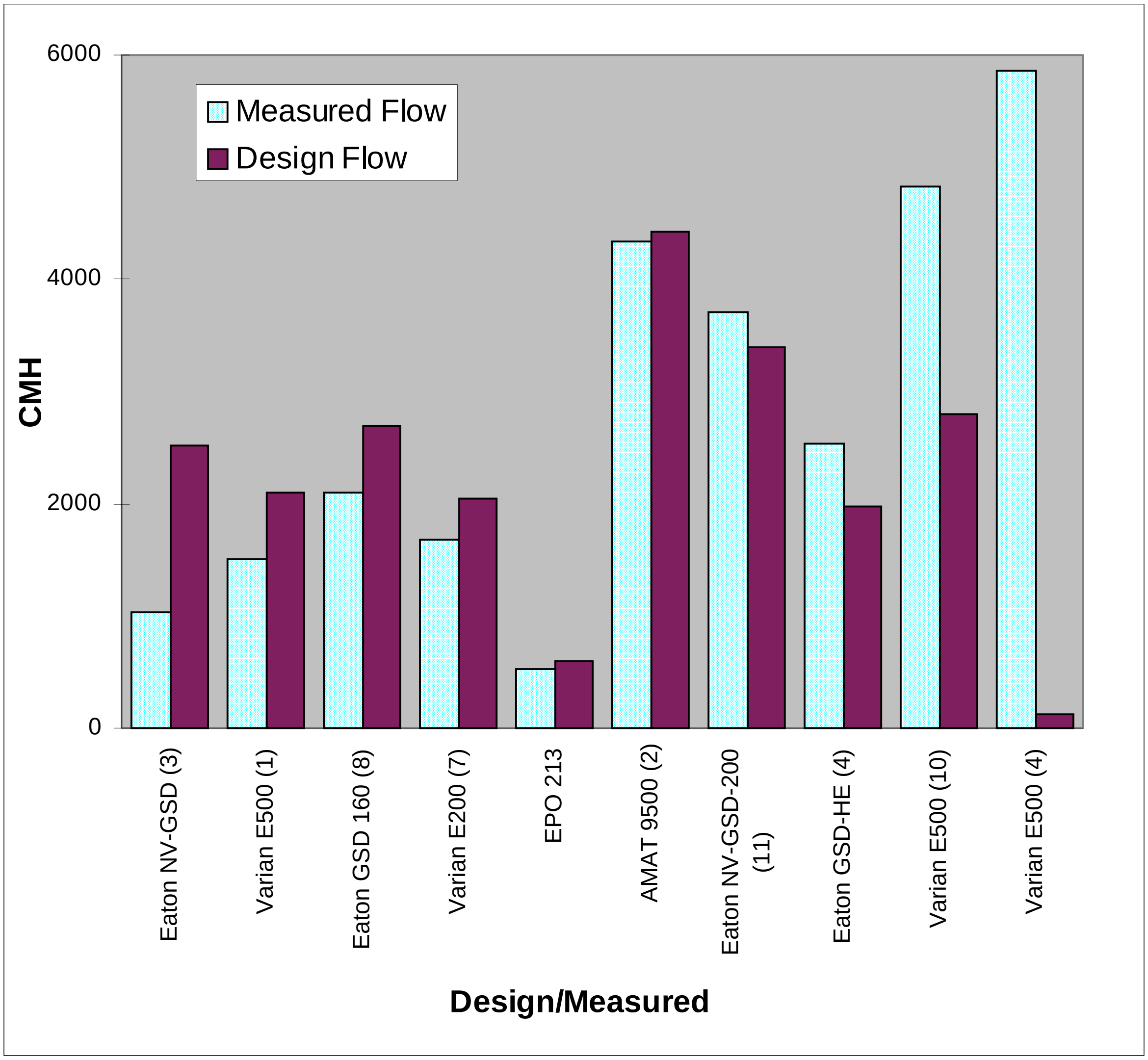
Dry Etch Process Area-Process Cooling Water



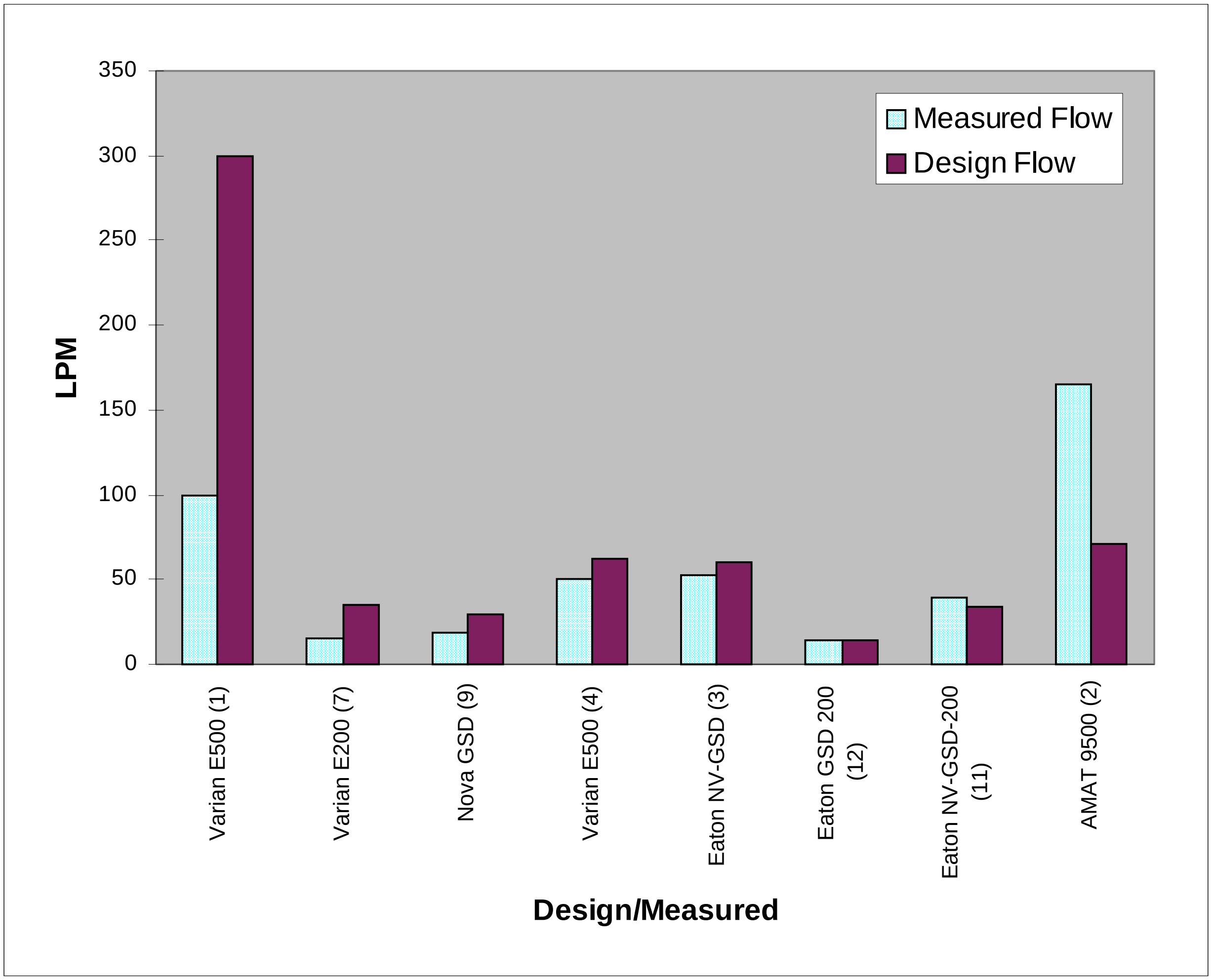
Dry Etch Process Area-UPW



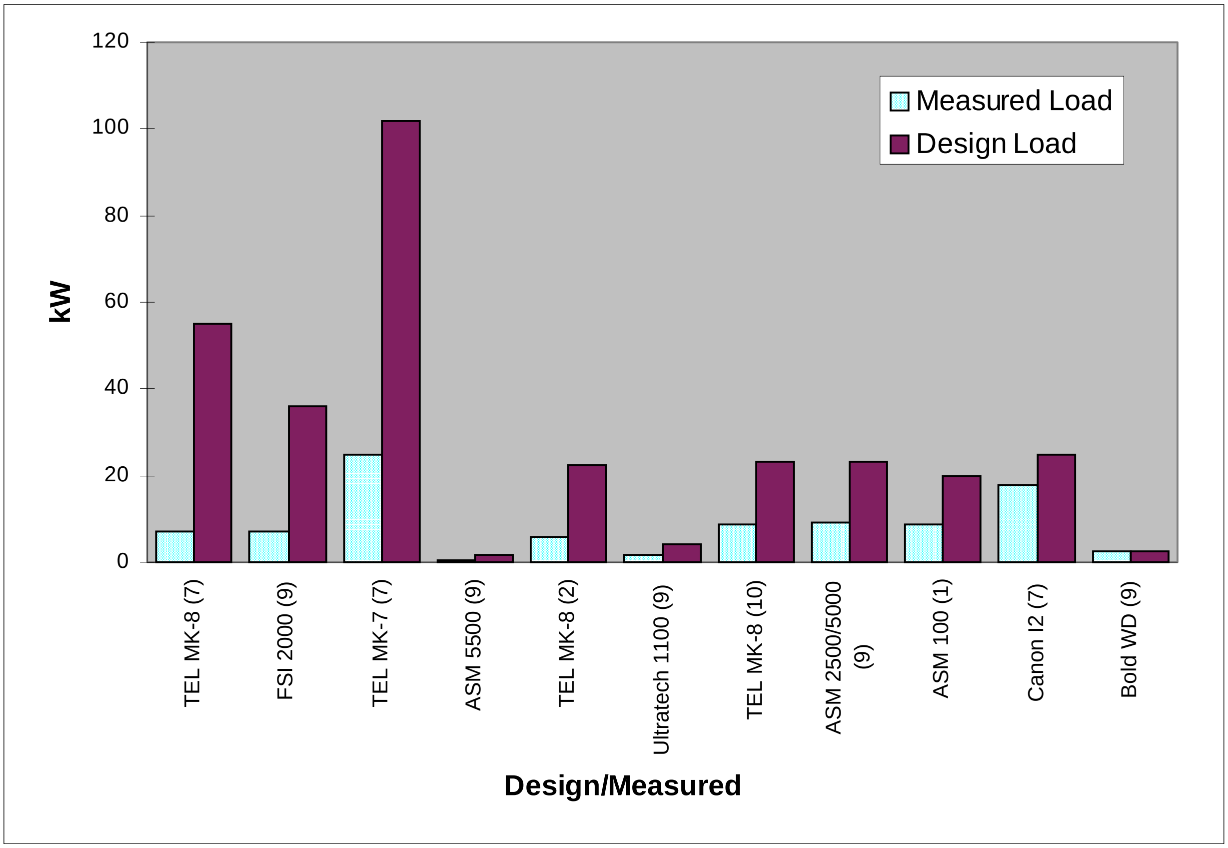
Implant Process Area-Electricity



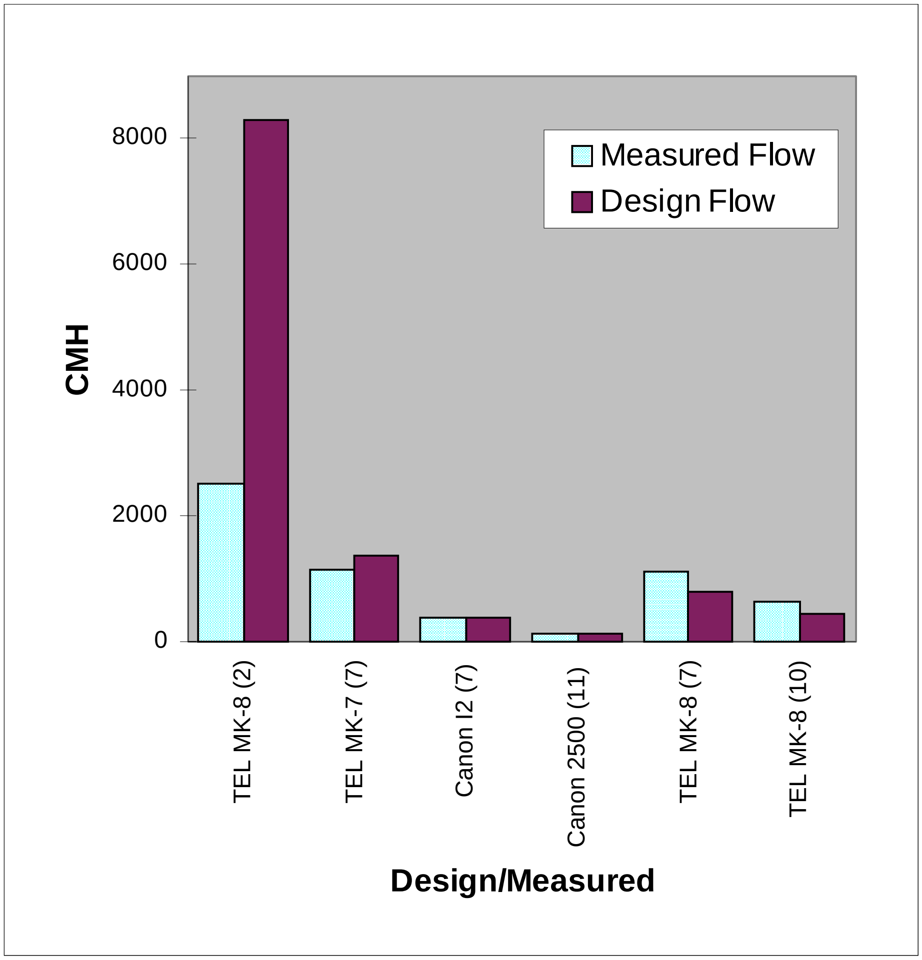
Implant Process Area-Exhaust



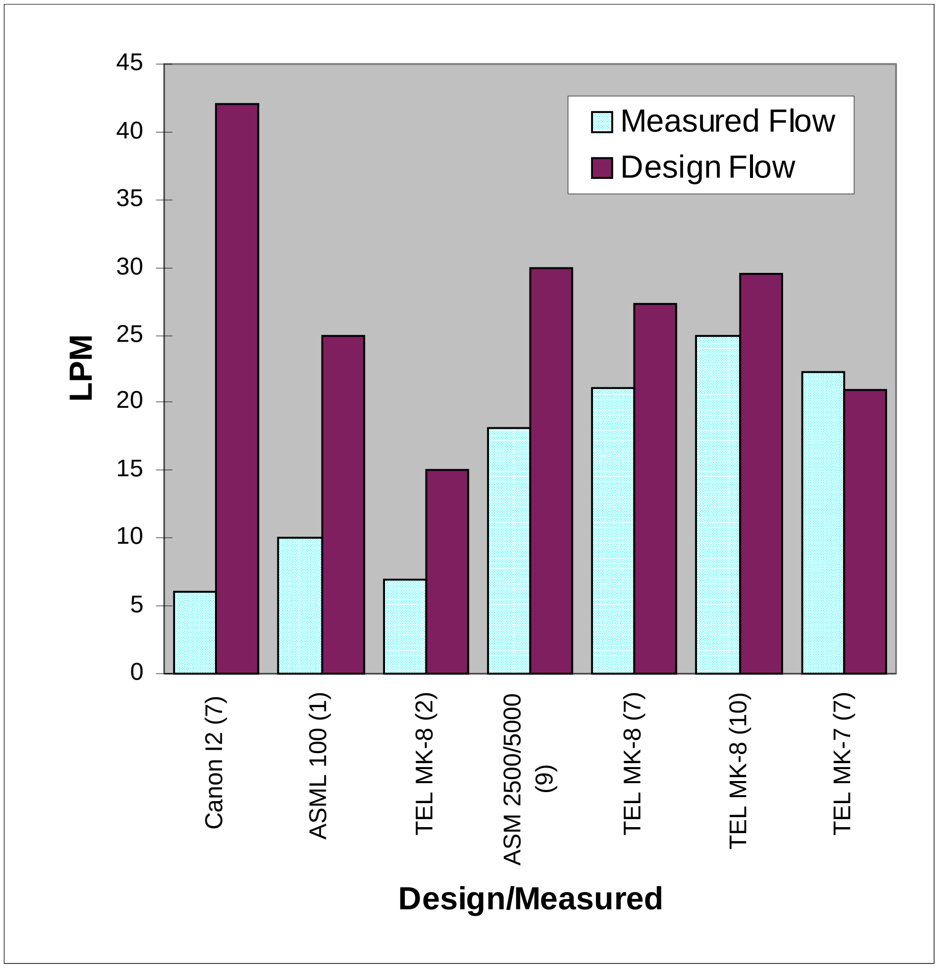
Implant Process Area-Process Cooling Water



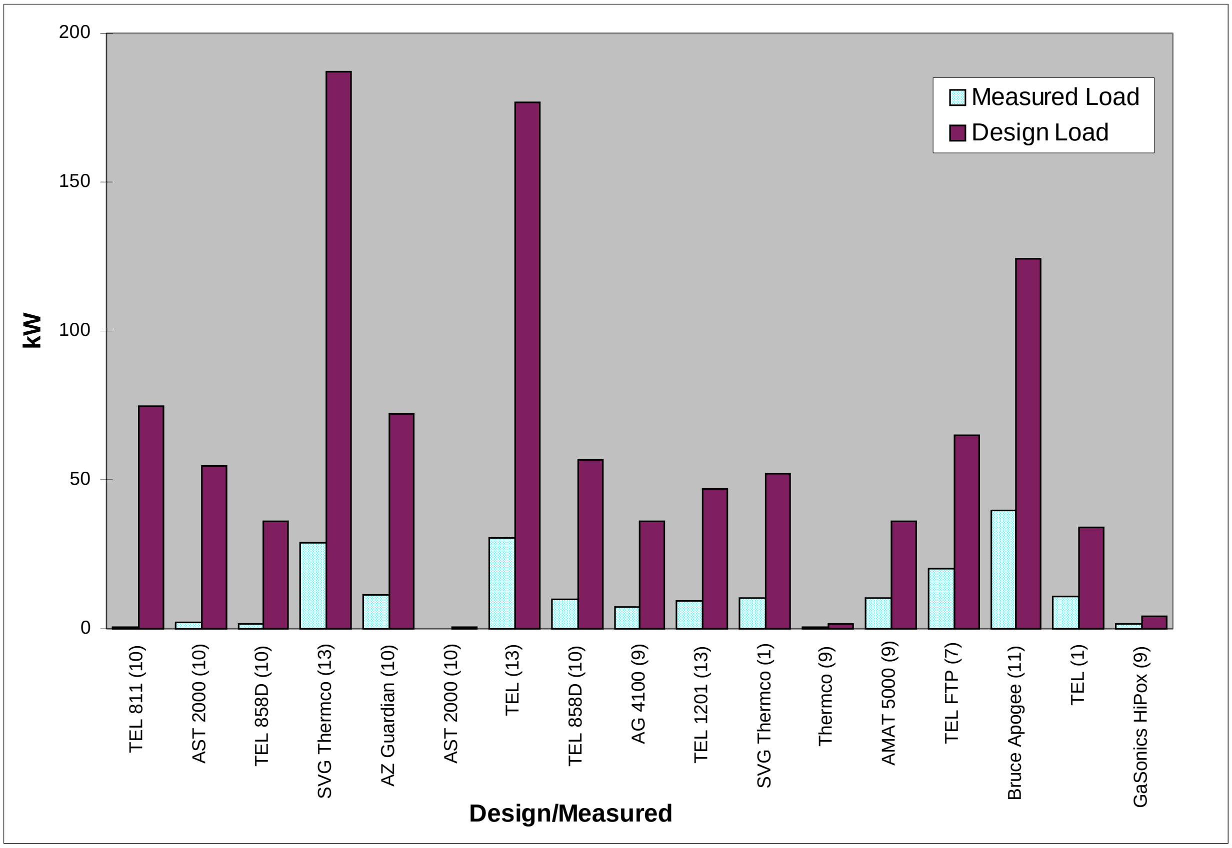
Patterning Process Area-Electricity



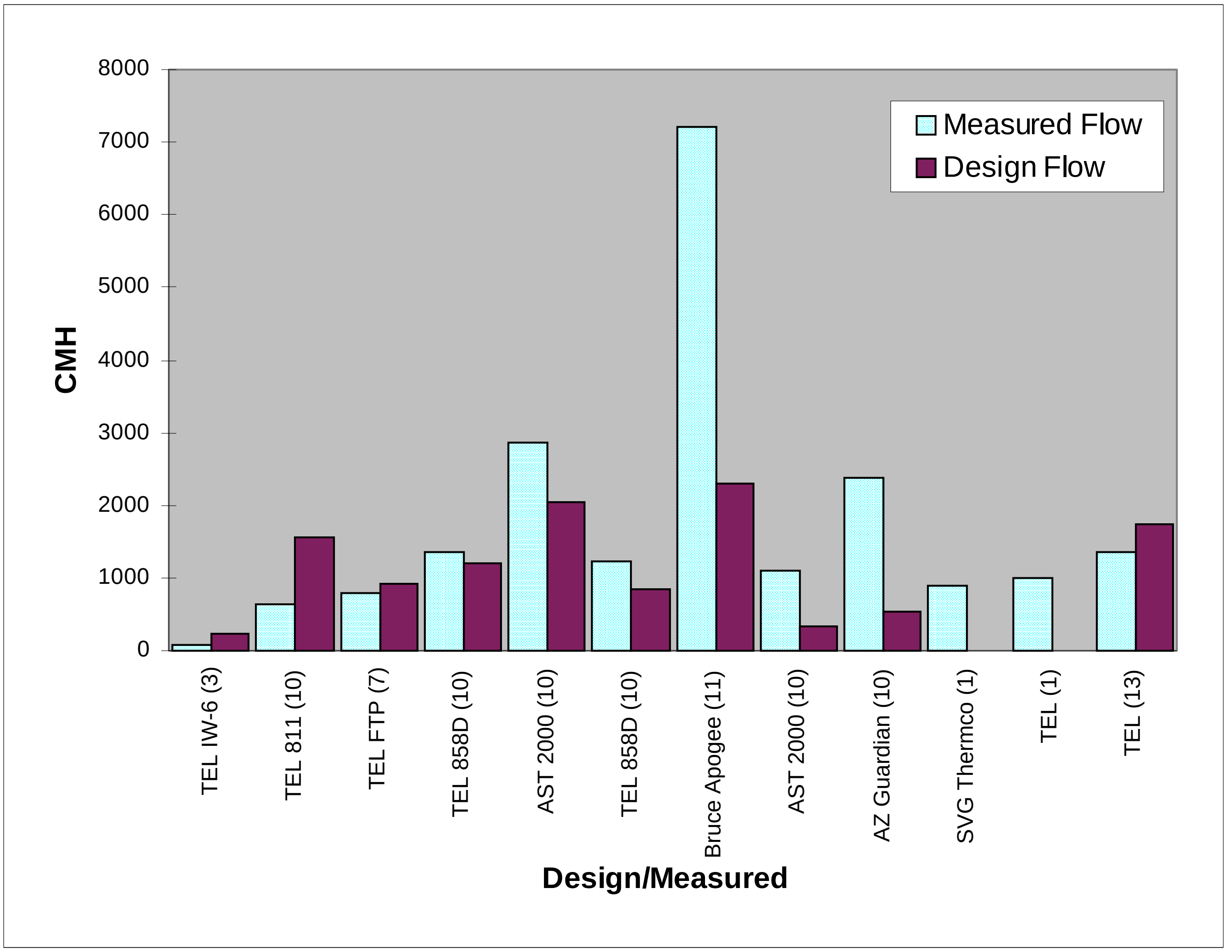
Patterning Process Area-Exhaust



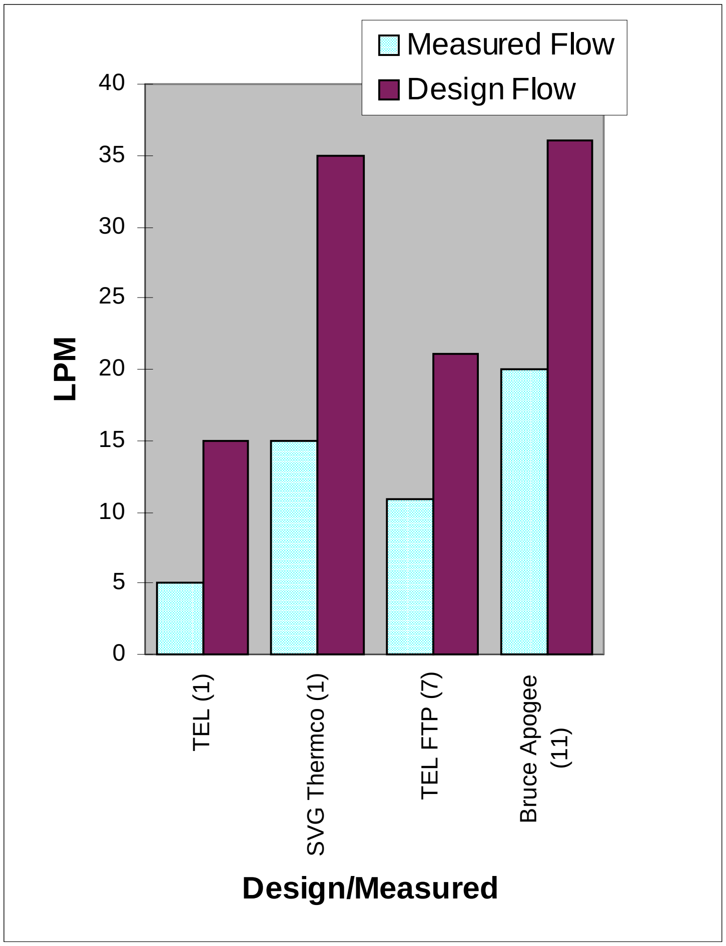
Patterning Process Area-Process Cooling Water



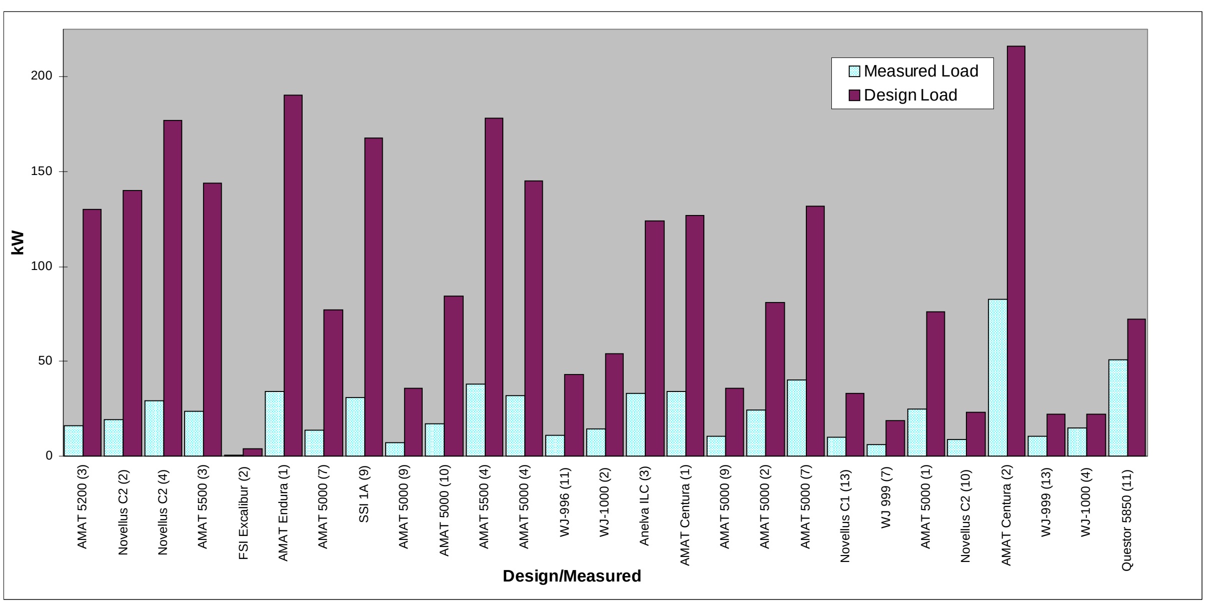
Thermal Process Area-Electricity



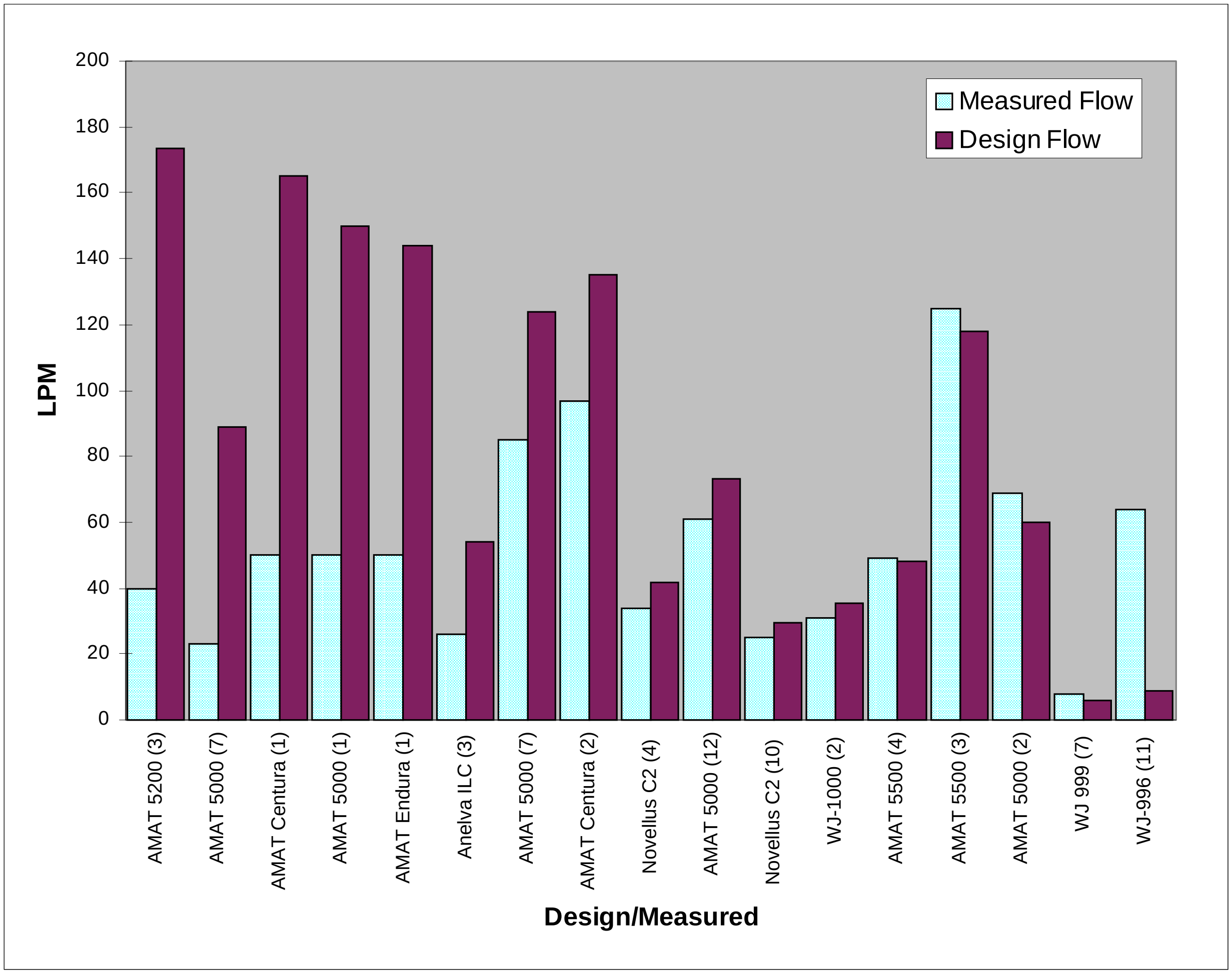
Thermal Process Area-Exhaust



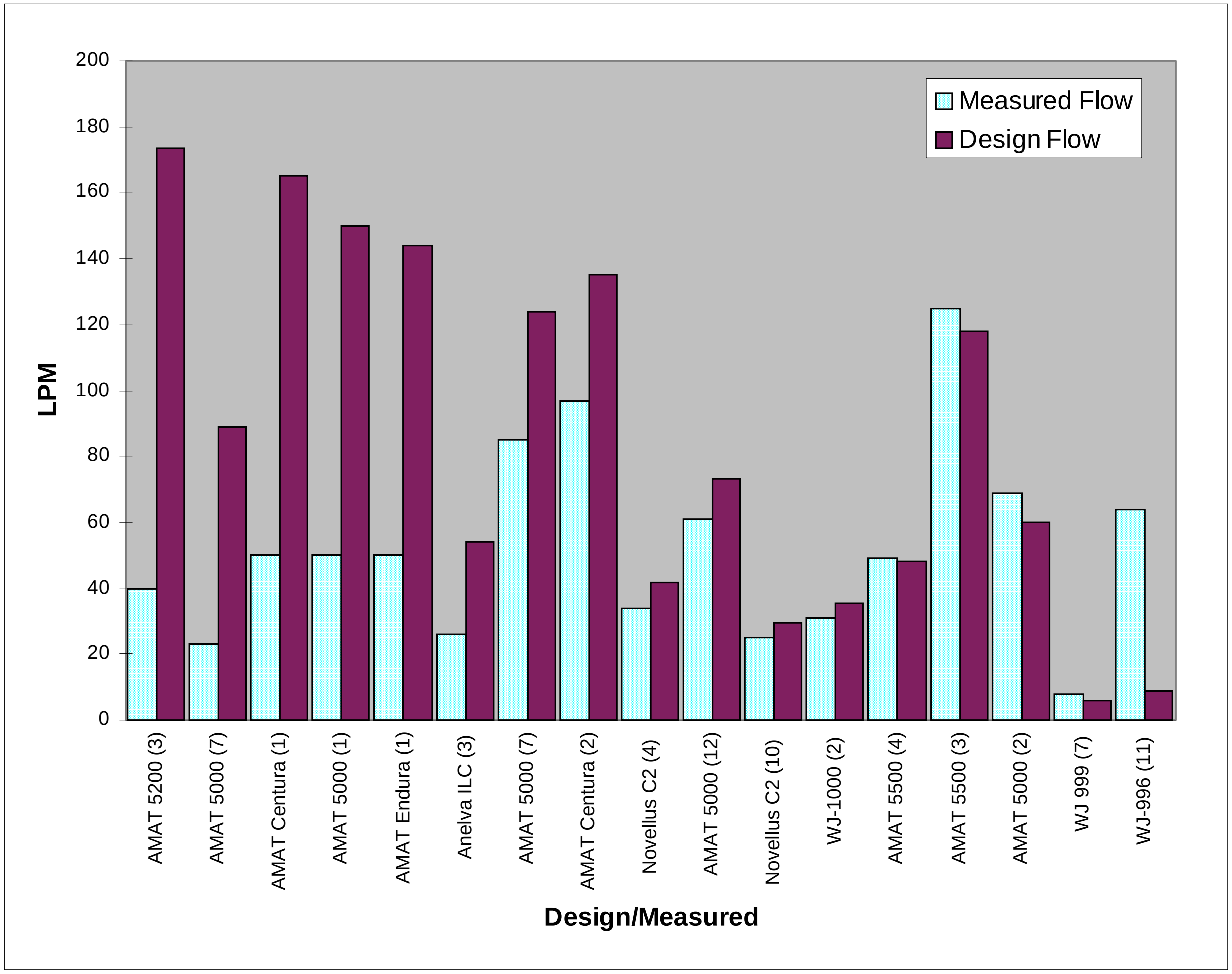
Thermal Process Area-Process Cooling Water



Thin Films Process Area-Electricity



Thin Films Process Area-Exhaust



Thin Films Process Area-Process Cooling Water

E

ENGLISH/METRIC METRIC/ENGLISH CONVERSIONS

To Obtain	**Multiply**	**By**
cfm	cmh	0.5889
ft/min.	m/min.	3.281
ft^2	m^2	10.76
ft^2/ton	m^2/ton	10.76
gallons	liters	0.2642
GPM	LPM	0.2642
GPM	LPH	15.852
in. H_2O	Pascal	0.00402
kW	BTU	3,413
^oF	^oC	1.8, then add 32
kW	tons of refrigeration	3.516
ft^3	m^3	35.316
CMH	CFM	1.6981
m/min.	ft/min.	0.3048
m^2	ft^2	0.0929
m2/ton	ft2/ton	0.0929
liters	gallons	3.785
LPM	GPM	3.785
LPH	GPM	0.0631
Pascal	in. H_2O	248.7562
BTU x 10^6	kW	0.00029
^oC	^oF	subtract 32, then multiply by 0.556
Tons of refrigeration	kW	0.2844
m^3	ft^3	0.0283

F

ESTIMATED SAVINGS FROM ENERGY CONSERVATION MEASURES FROM INDIVIDUAL FACILITIES

The following tables present estimates of savings resulting from energy conservation measures at each participating fab that reported data. The data in the tables are summarized for all fabs in the first figure. All of the data presented in these tables were reported by participating fabs. To the extent possible, Planergy has presented the data in a consistent manner in these tables, including translating savings reported in foreign currencies to U.S. dollars when necessary. Blank spaces in the tables indicate data that were not reported or, in the case of simple payback, values that cannot be calculated based on the data reported.

Each table presents a description of each energy conservation measure, the capital cost of the measure, the estimated annual savings, and the simple payback. Capital cost refers to the one-time investment required to implement the energy conservation measure. Estimated annual savings refers to the decrease in the cost of energy per year expected to result from the energy conservation measure. Simple payback is a value calculated from the capital cost divided by the estimated annual savings, and is used to approximate the number of years required for the energy conservation measure to pay for itself.

Summary of Energy Conservation Measures Reported by Fabs

Facility	Capital Cost	Estimated Annual Savings US Dollars	Simple Payback years
A	$252,500	$574,180	0.44
B	$2,074,000	$791,278	2.60
C		$1,450,180	
D	$715,000	$5,825,000	0.12
E	$0	$123,649	immediate
F		$2,397,896	
Total		**$11,162,183**	

Energy Conservation Measures Reported by Fab A

Description of Energy Conservation Measures	Capital Cost	Estimated Annual Savings US Dollars	Simple Payback years
Chiller Sequencing	$40,000	$132,060	0.30
Condenser Water Temperature Re	$25,000	$78,645	0.30
Makeup Air Optimization	$36,000	$29,411	1.20
Makeup Air Temperature Reset	$35,000	$199,000	0.20
Compressed Air	$5,500	$21,900	0.25
Lighting	$73,000	$34,548	2.10
Supply Air Reset	$38,000	$78,616	0.48
Total *	**$252,500**	**$574,180**	**0.44**

* Total costs and savings are shown, but some overlap potential exists.
Note: Savings are based on standard unit costs of $0.05/kWh, $3MCF gas.

Energy Conservation Measured Reported by Fab B

Description of Energy Conservation Measures	Capital Cost	Estimated Annual Savings US Dollars	Simple Payback years
Chiller Sequencing	$139,750	$111,303	1.30
Makeup Air Optimization	$27,500	$10,038	2.70
Condenser Water Temp. Reset	$47,500	$81,600	0.60
Supply Air Reset	$40,000	$61,587	0.60
Secondary Chilled Water Flow Reduction	$228,000	$15,455	15.00
Air Compressor Sequencing	$12,000	$9,286	1.30
Reheat Reduction	$186,750	$71,812	2.60
Humidification Reduction	$37,500	$54,007	0.70
Reheat System Modifications**	$40,000	($39,157)	-1.00
Process Coling Water Alternate Cooling	$120,000	$45,120	2.70
Cogeneration	$1,150,000	$330,000	3.50
Variable Frequency Drive Additions	$45,000	$40,227	1.10
Total *	**$2,074,000**	**$791,278**	**2.60**

* Total Costs and savings are shown but overlap potential exists.
** Annual savings are affected by savings for ECMs 3 and 11.
Note: Savings are based on site specific unit costs.

Energy Conservation Measures Reported by Fab C

Description of Energy Conservation Measures	Capital Cost	Estimated Annual Savings US Dollars	Simple Payback years
DI/UPW Plant	not provided	$198,830	
Chiller Plant 5C and 12C Optimization	not provided	$249,268	
Chiller Plant 5C and 12C Tower Cooling Modification	not provided	$182,352	
Chiller Plant 12C Chiller Replacement	not provided	$155,089	
DFU Volume Reduction	not provided	$558,581	
Chiller Plant 12C Thermal Storage System	not provided	$87,138	
Boiler Exhaust/ Blow Down Recovery	not provided	$18,922	
Total		**$1,450,180**	

Energy Conservation Measures Reported by Fab D

Description of Energy Conservation Measures	Capital Cost	Estimated Annual Savings US Dollars	Simple Payback years
Lighting Retrofit	$122,000	$46,000	2.65
Exhaust Heat Recovery at Chem Dock	$130,000	$245,000	0.53
Variable Frequency Drives on RO Turbine Pumps	$100,000	$82,000	1.22
Turn off Glycol Chiller	$4,000	$14,000	0.29
Variable Frequency Drives on Admin. Air Handlers	$24,000	$8,000	3.00
Reduce Vertical Laminar Flow Airflow	$10,000	$246,000	0.04
Chiller Condenser Water Reset	$5,000	$53,000	0.09
Replace Glycol Chiller	$260,000	$70,000	3.71
Optimize Glycol Coil/Humidification	$50,000	$27,000	1.85
Air Compressor Waste Heat Recovery	$10,000	$60,000	0.17
Total	**$715,000**	**$5,825,000**	**0.12**

* Based on $0.05/kWh

Energy Conservation Reported by Fab E

Description of Energy Conservation Measures	Capital Cost	Estimated Annual Savings US Dollars	Simple Payback years
Chillers sequencing adjustment	none	$18,583	Immediate
Cleaning of the brass tubes in chillers	none	$87,225	Immediate
Adjustment of outside air conditioners	none	$8,008	Immediate
Adjustment on power factors	none	$9,833	Immediate
Total		**$123,649**	

Note: US Dollars converted from New Taiwan Dollars at 0.03092 $NT/$US, per exchange rate in Wall Street Journal December 9, 1998.

Energy Conservation Measures Reported by Fab F

Description of Energy Conservation Measures	Capital Cost	Estimated Annual Savings US Dollars	Simple Payback years
De-Ionized Water Plant		$789,640	
Acid Exhaust		$36,826	
General Exhaust		$11,470	
Caustic Exhaust		$13,281	
Solvent Exhaust		$2,415	
N2 & PN2		$146,699	
Helium		$185,940	
Argon		$28,978	
Hydrogen		-$20,526	
Process Cooling Water Consumption		$7,244	
MAU		$155,151	
Bulk Solvent/IPA		$20,526	
Total Chemical		$1,020,253	
Reclaim Inlet TOC		NIL	
Chilled Water Load		NA	
Total		**$2,397,896**	

Note: Number in brackets implies cost increase

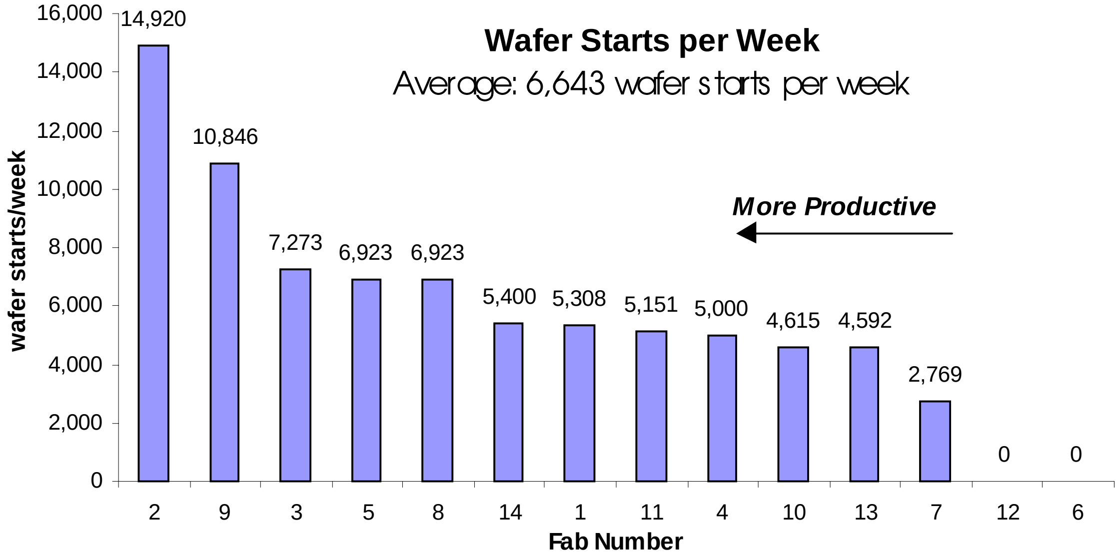
G
ADDITIONAL SCATTER PLOTS AND BAR CHARTS

The scatter plots in this appendix explore the relationships between fab energy efficiency, fab age, average annual temperature, location, and type. In addition to the raw data, many of the scatter plots also present the least-squares regression line, the least squares regression equation, and the r-square statistic for each regression.* In general, the relationships between variables on a one-to-one basis (as shown in the scatter plots) are fairly weak by the standards of statistical analysis. The strongest relationship (r-square of 0.26) is shown in the plot of chiller plant kWh/unit of production versus average annual temperature. Multivariate regression techniques would yield higher values of r-square.

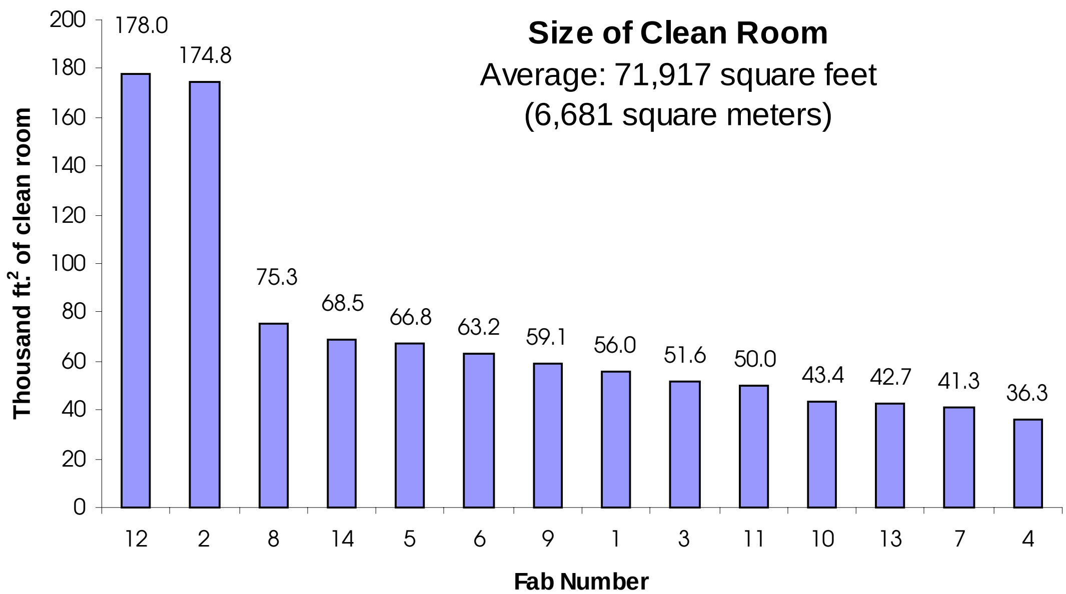
This appendix also presents bar charts showing flow rate (gpm or cfm) per unit of production statistics for each of the 14 fabs studied. Although a low average flow rate per unit of production is an indicator of energy efficiency, this is not necessarily the appropriate conclusion. Differences in the efficiency of a fab's pumping units or fans may allow a fab with a higher average flow rate to be using its energy resources more efficiently, even as it uses resources such as water or air more inefficiently than other fabs.

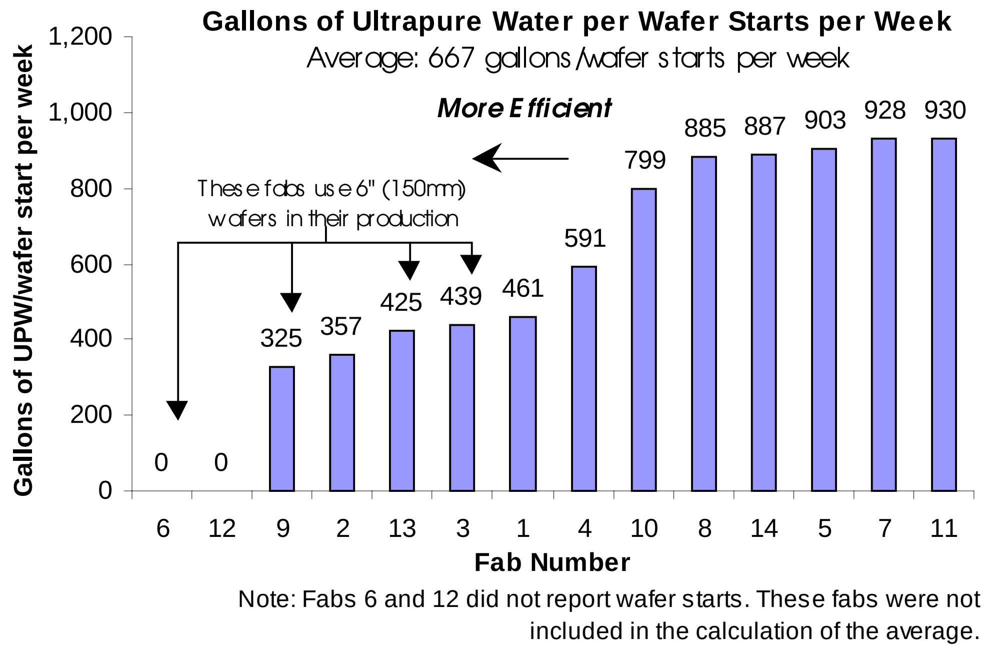
Finally, this appendix presents a number of other bar charts that were not included in the body of this report. Fab engineering staff may find these charts to be helpful in interpreting and drawing conclusions from other information in this report.

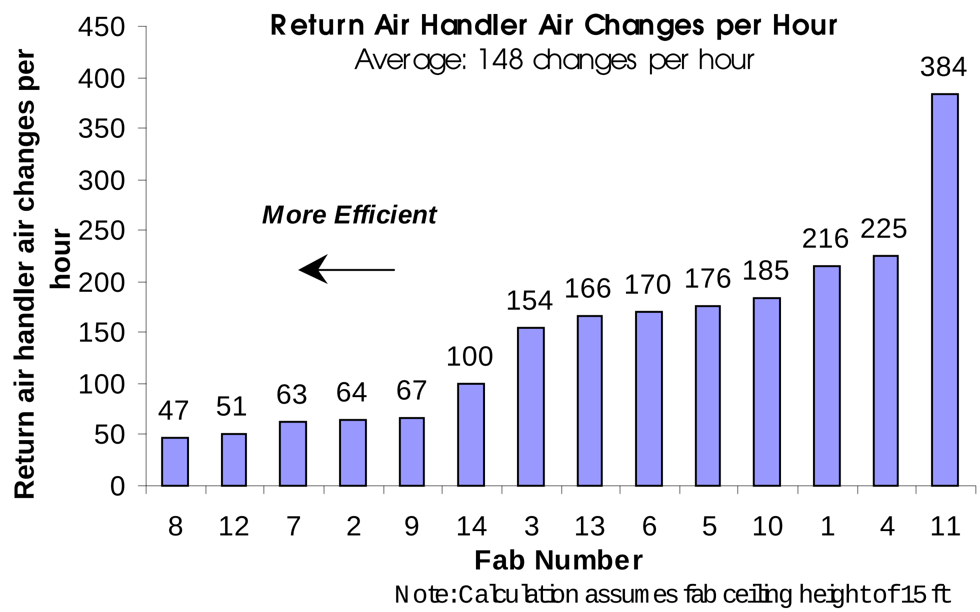
* The r-square statistic is a measure of goodness of fit. It represents the amount of variation in the y values that is explained by the variation in x values.

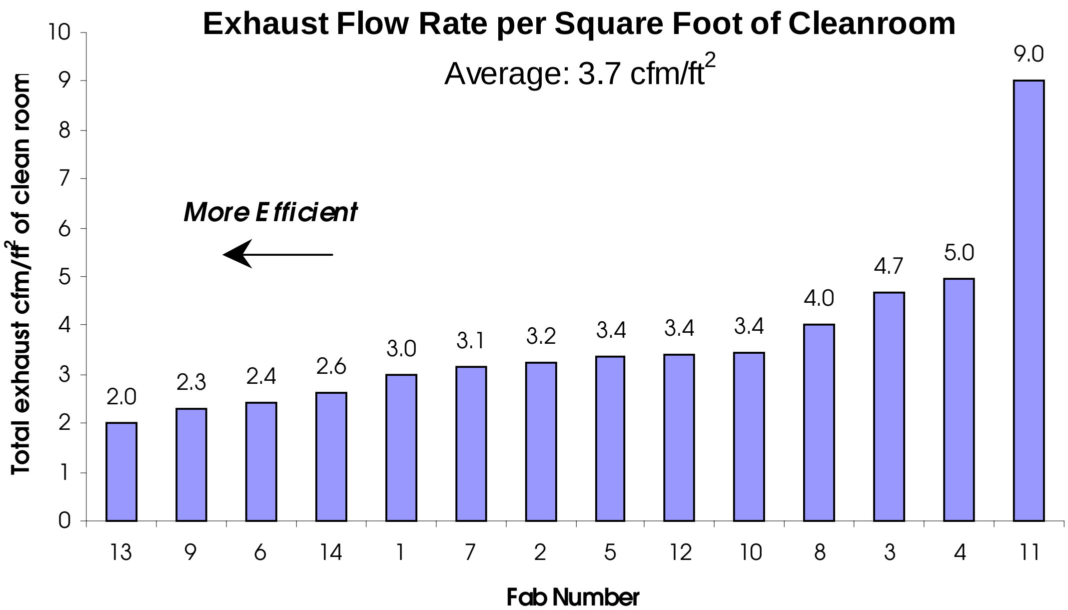


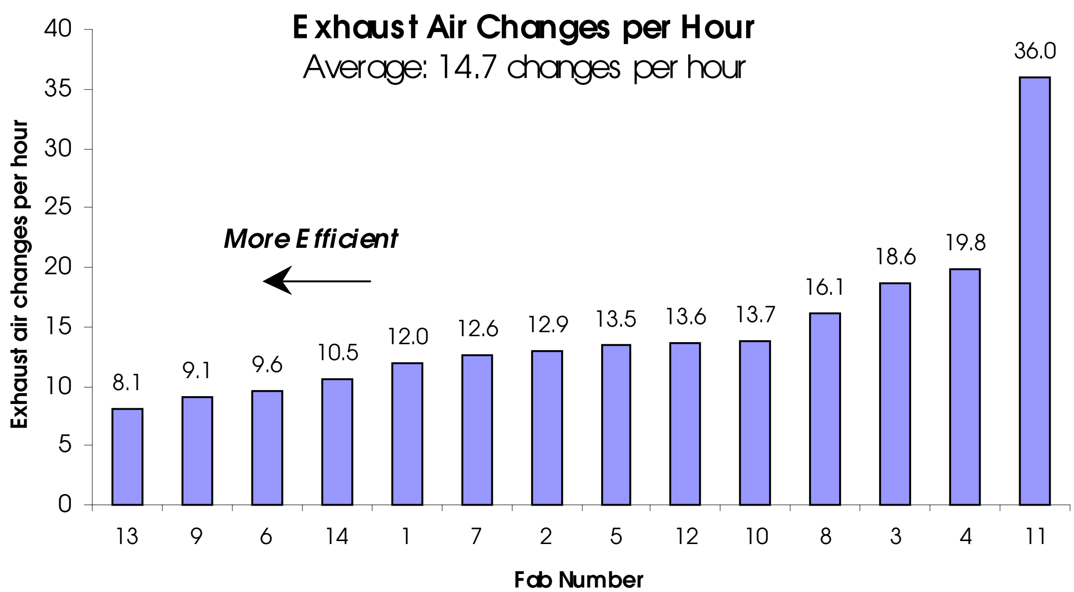
Note: Fab 12 did not report wafer starts. Data for fab 6 is confidential. Neither fab was included in the calculation of the average.



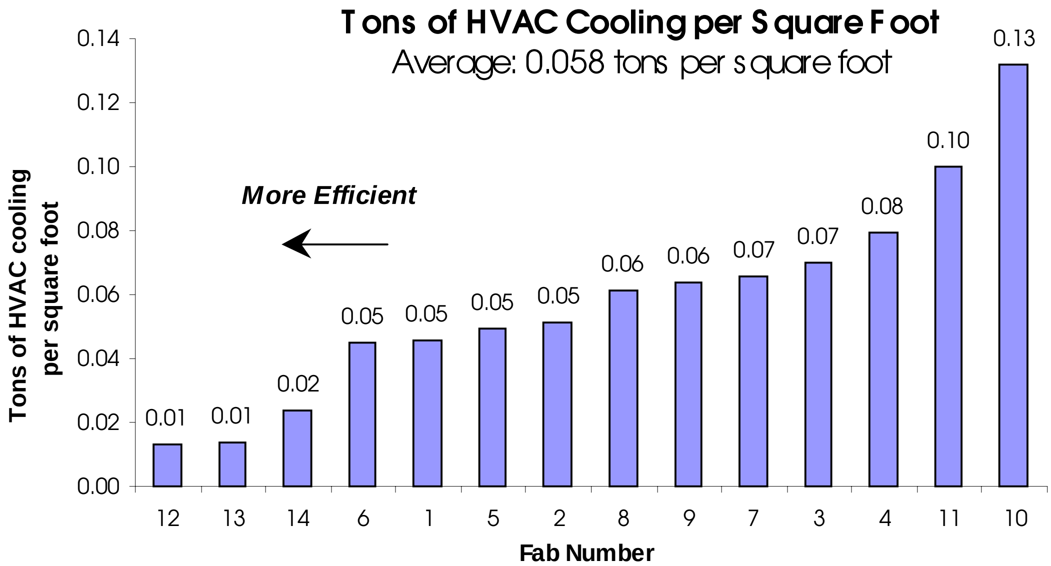

Gallons of Ultrapure Water per Wafer Starts per Week
Average: 667 gallons/wafer starts per week
More Efficient
These fabs use 6" (150mm) wafers in their production
Gallons of UPW/wafer start per week
1,200
1,000
800
600
400
200
0
0
0
325
357
425
439
461
591
799
885
887
903
928
930
6
12
9
2
13
3
1
4
10
8
14
5
7
11
Fab Number
Note: Fabs 6 and 12 did not report wafer starts. These fabs were not included in the calculation of the average.

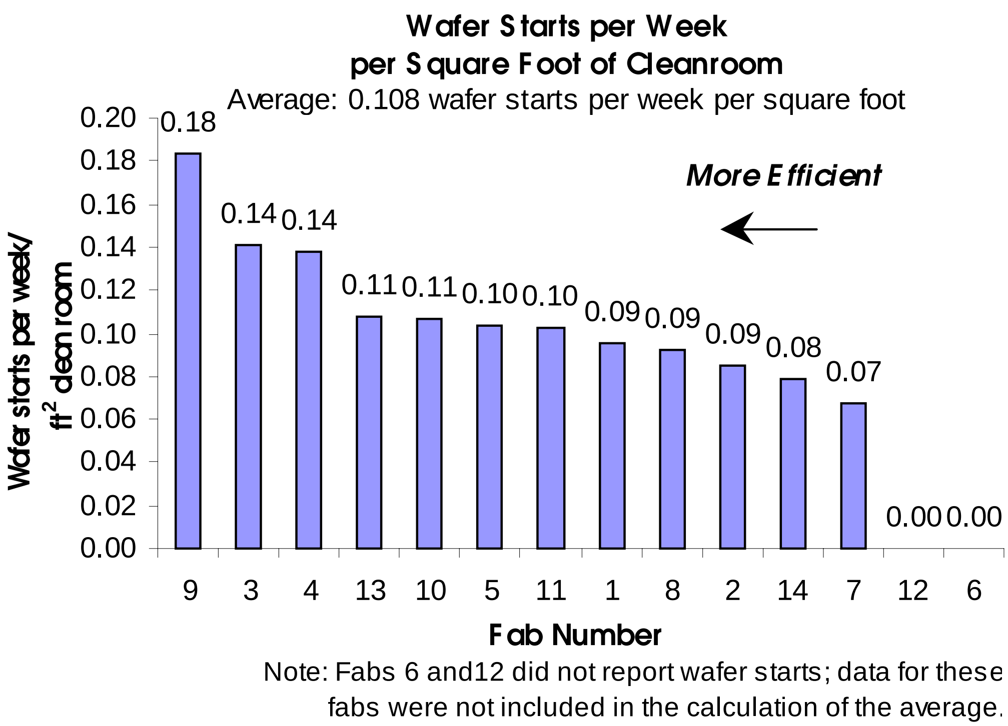

Return Air Handler Air Changes per Hour
Average: 148 changes per hour
More Efficient
Return air handler air changes per hour
450
400
350
300
250
200
150
100
50
0
47
51
63
64
67
100
154
166
170
176
185
216
225
384
8
12
7
2
9
14
3
13
6
5
10
1
4
11
Fab Number
Note: Calculation assumes fab ceiling height of 15 ft

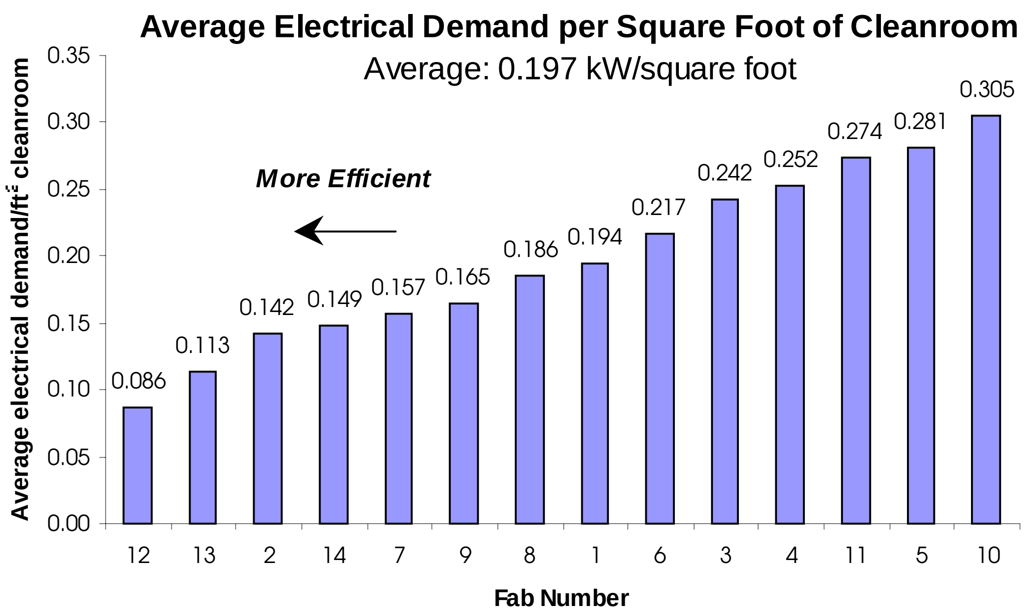


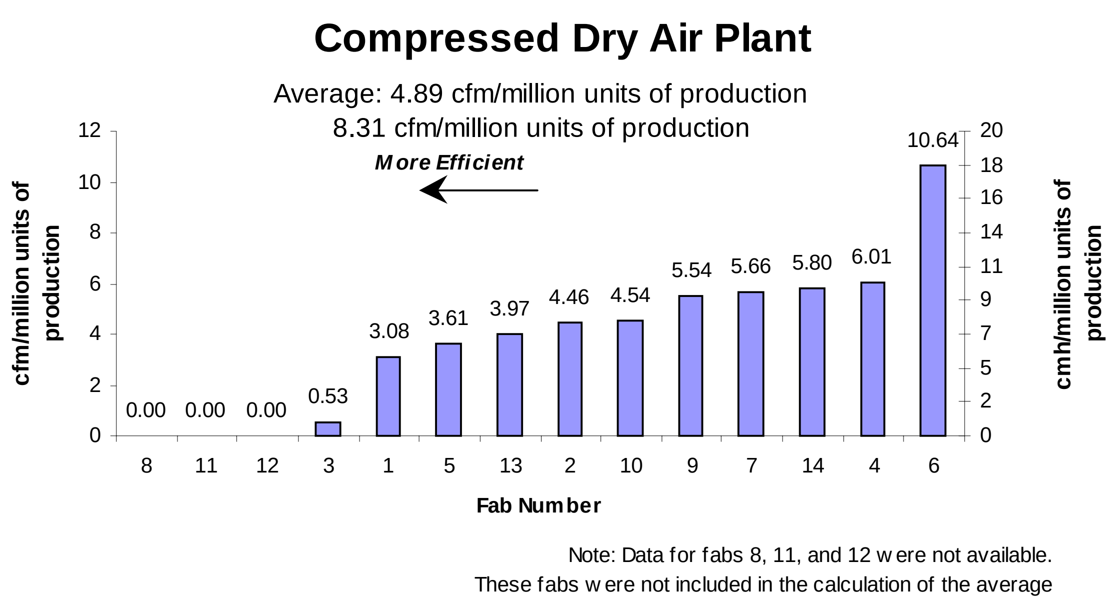


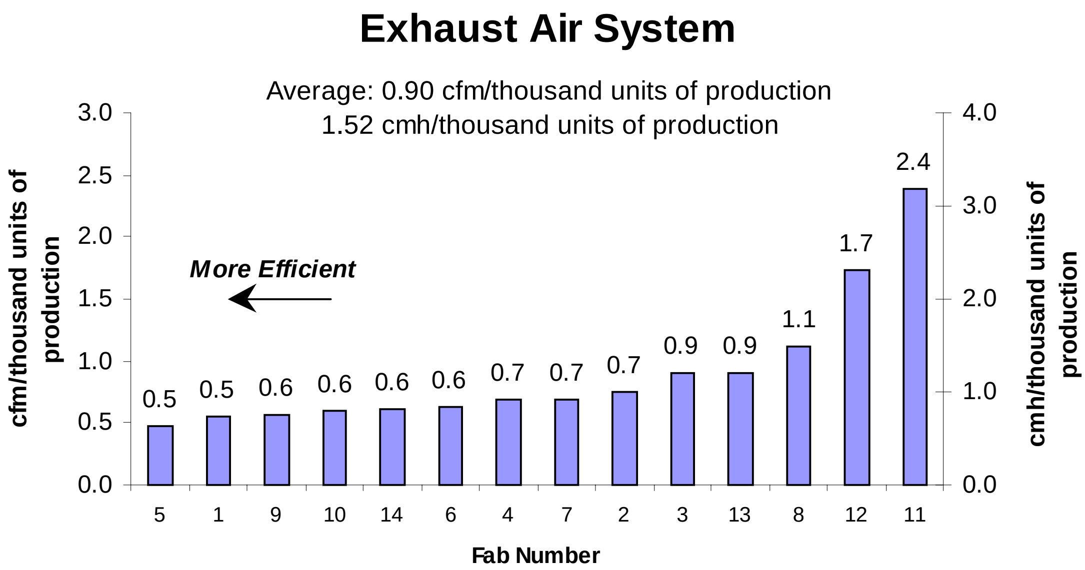
Note: Calculation assumes fab ceiling height of 15 ft.

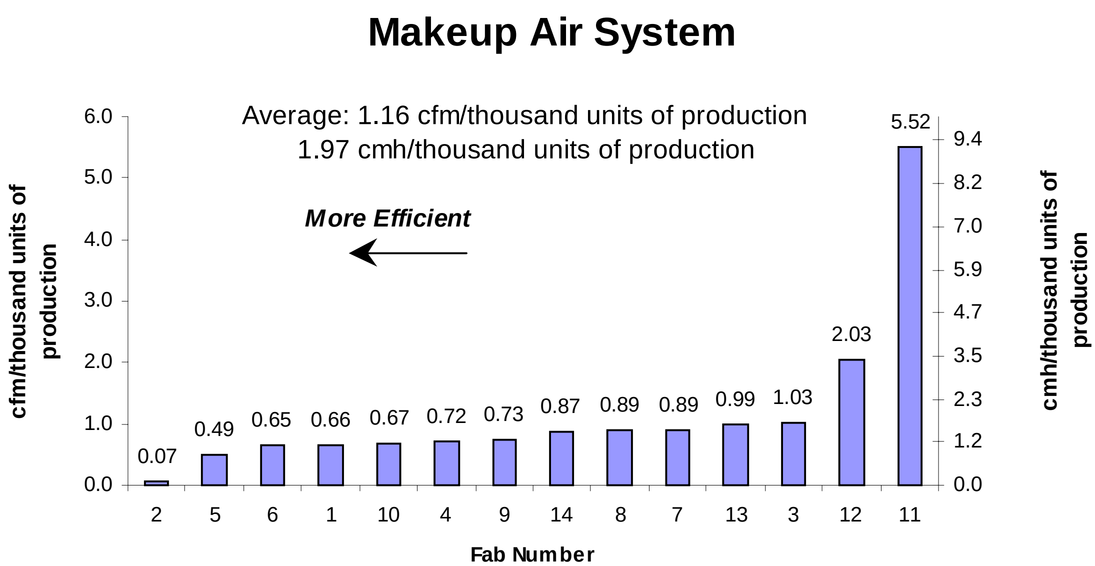

Tons of HVAC Cooling per Square Foot
Average: 0.058 tons per square foot
Tons of HVAC cooling per square foot
More Efficient
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.01
0.01
0.02
0.05
0.05
0.05
0.05
0.06
0.06
0.07
0.07
0.08
0.10
0.13
12
13
14
6
1
5
2
8
9
7
3
4
11
10
Fab Number


Wafer Starts per Week
per Square Foot of Cleanroom
Average: 0.108 wafer starts per week per square foot
Wafer starts per week/
ft² clean room
More Efficient
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.18
0.14
0.14
0.11
0.11
0.10
0.10
0.09
0.09
0.09
0.08
0.07
0.00
0.00
9
3
4
13
10
5
11
1
8
2
14
7
12
6
Fab Number
Note: Fabs 6 and12 did not report wafer starts; data for these
fabs were not included in the calculation of the average.


Average Electrical Demand per Square Foot of Cleanroom
Average: 0.197 kW/square foot
More Efficient
Average electrical demand/ft² cleanroom
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.086
0.113
0.142
0.149
0.157
0.165
0.186
0.194
0.217
0.242
0.252
0.274
0.281
0.305
12
13
2
14
7
9
8
1
6
3
4
11
5
10
Fab Number

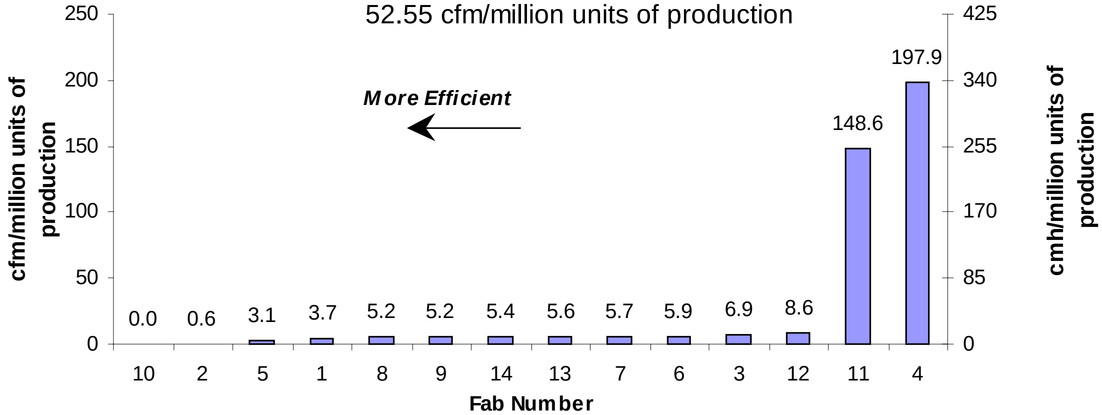

Compressed Dry Air Plant
Average: 4.89 cfm/million units of production
8.31 cfm/million units of production
More Efficient
cfm/million units of production
cmh/million units of production
12
10
8
6
4
2
0
20
18
16
14
11
9
7
5
2
0
0.00
0.00
0.00
0.53
3.08
3.61
3.97
4.46
4.54
5.54
5.66
5.80
6.01
10.64
8
11
12
3
1
5
13
2
10
9
7
14
4
6
Fab Number
Note: Data for fabs 8, 11, and 12 were not available.
These fabs were not included in the calculation of the average


Exhaust Air System
Average: 0.90 cfm/thousand units of production
1.52 cmh/thousand units of production
More Efficient
cfm/thousand units of production
cmh/thousand units of production
Fab Number
5 1 9 10 14 6 4 7 2 3 13 8 12 11
0.5 0.5 0.6 0.6 0.6 0.6 0.7 0.7 0.7 0.9 0.9 1.1 1.7 2.4
0.0 0.5 1.0 1.5 2.0 2.5 3.0
0.0 1.0 2.0 3.0 4.0


Makeup Air System
Average: 1.16 cfm/thousand units of production
1.97 cmh/thousand units of production
More Efficient
cfm/thousand units of production
cmh/thousand units of production
Fab Number
2 5 6 1 10 4 9 14 8 7 13 3 12 11
0.07 0.49 0.65 0.66 0.67 0.72 0.73 0.87 0.89 0.89 0.99 1.03 2.03 5.52
0.0 1.0 2.0 3.0 4.0 5.0 6.0
0.0 1.2 2.3 3.5 4.7 5.9 7.0 8.2 9.4

Nitrogen Plant

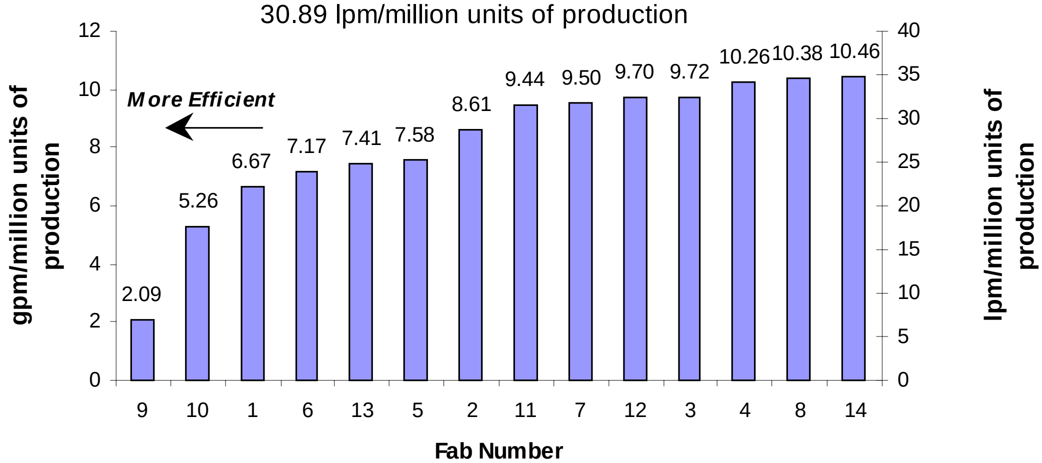
Average: 30.94 cfm/million units of production
52.55 cfm/million units of production



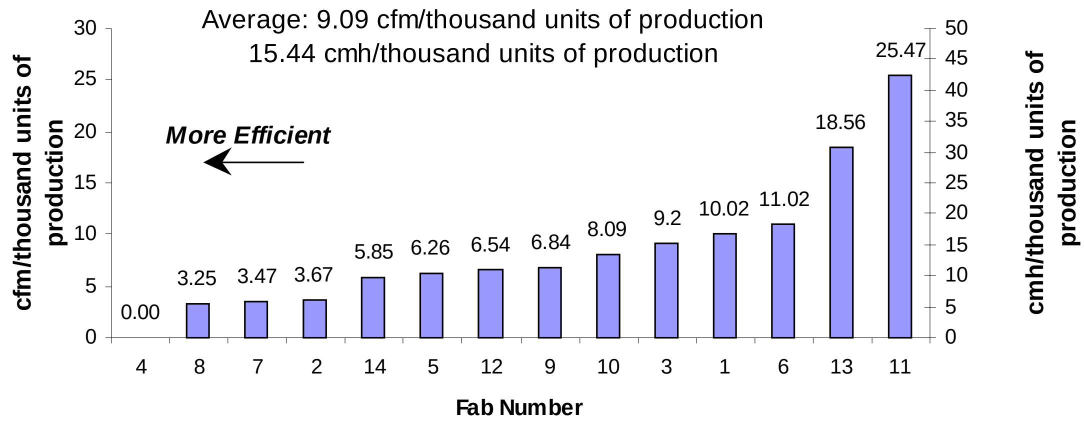
Note: Data for fab 10 was not available, and was not included in the calculation of the average.

Process Cooling Water

Average: 8.16 gpm/million units of production
30.89 lpm/million units of production

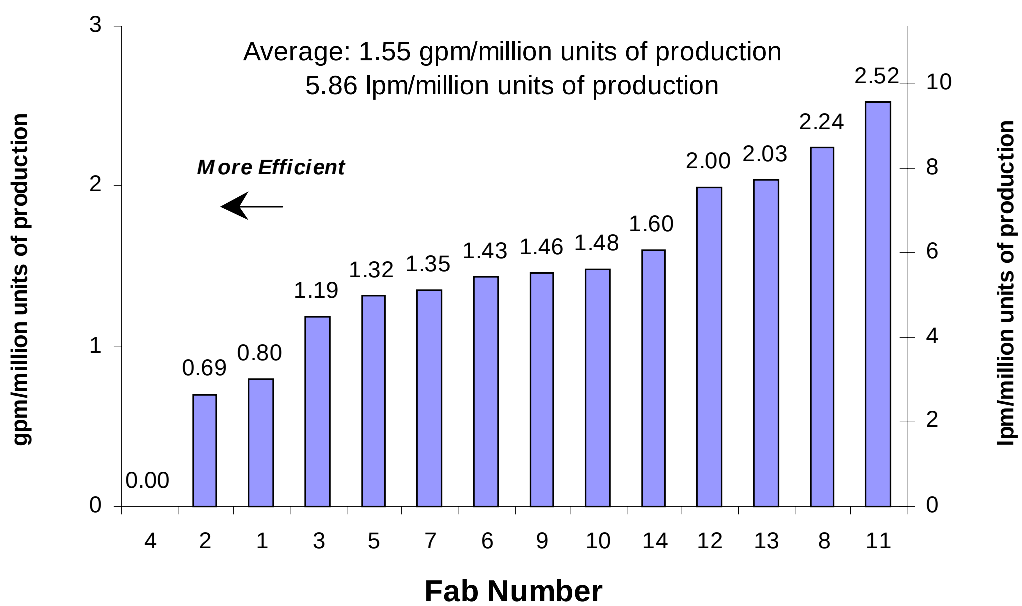


Recirculating Air System

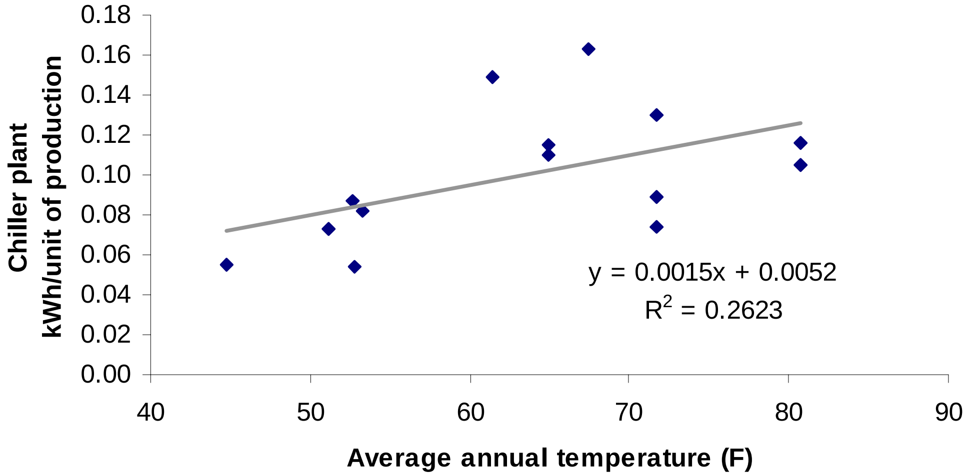


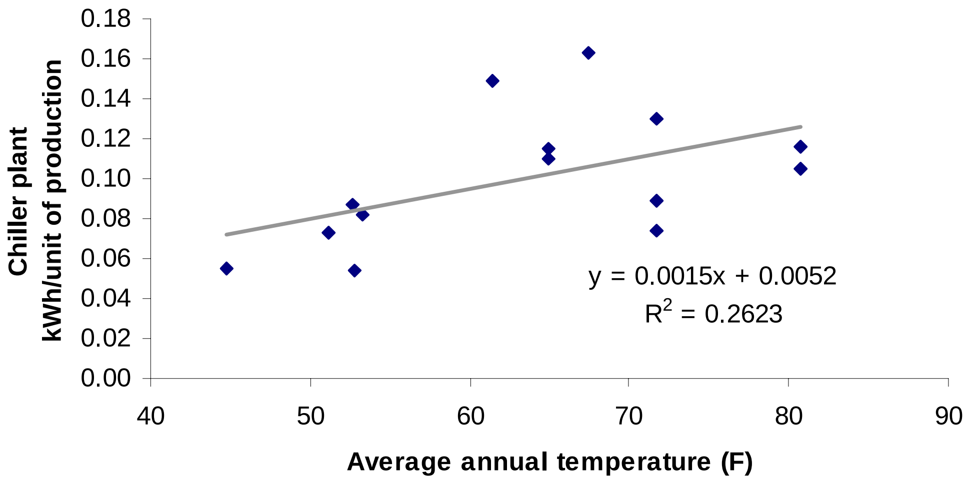
Note: Value for fab 4 is very small and does not show on the chart; fab 4 was not included in the calculation of the

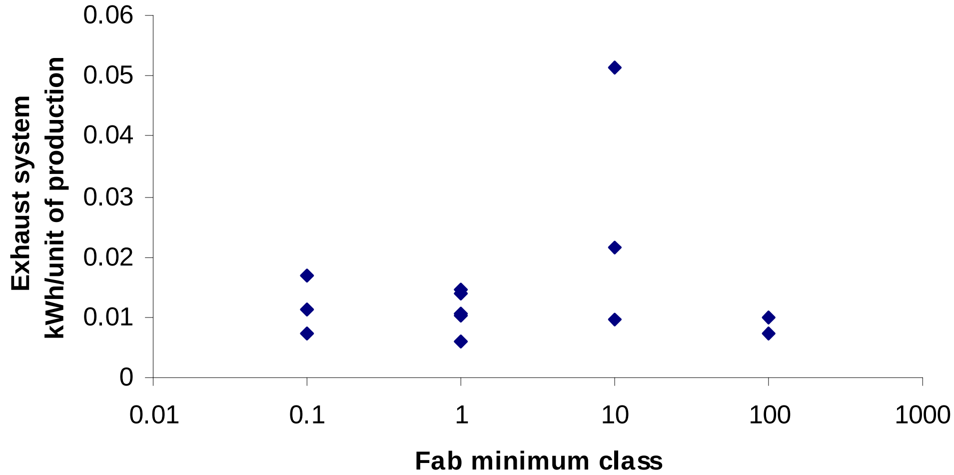
Ultra Pure Water

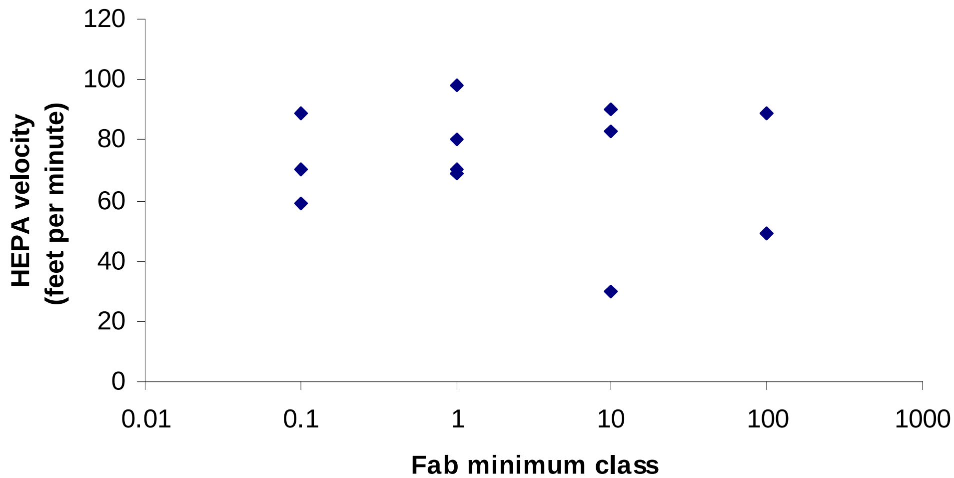


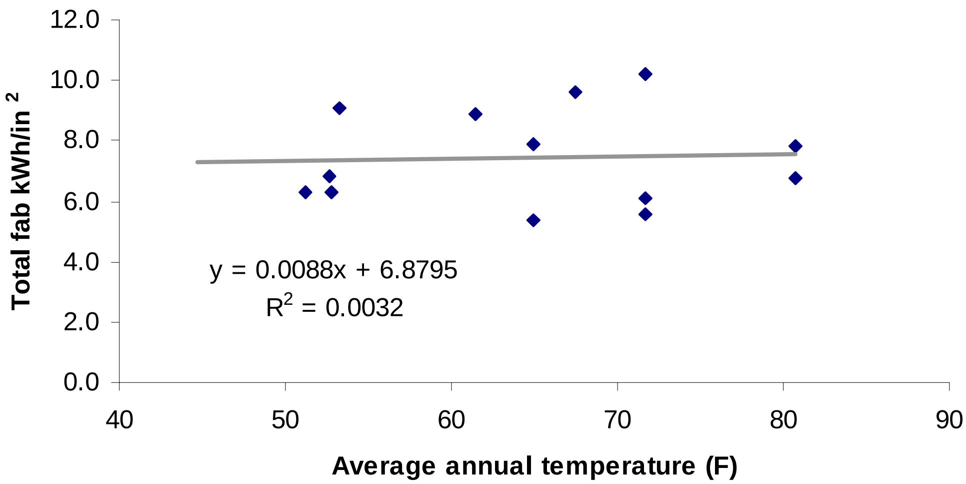
Note: Fab 9 did not report gpm and w as not included in the calculation of the average.


0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Chiller plant
kWh/unit of production
y = 0.0015x + 0.0052
R^2 = 0.2623
40
50
60
70
80
90
Average annual temperature (F)

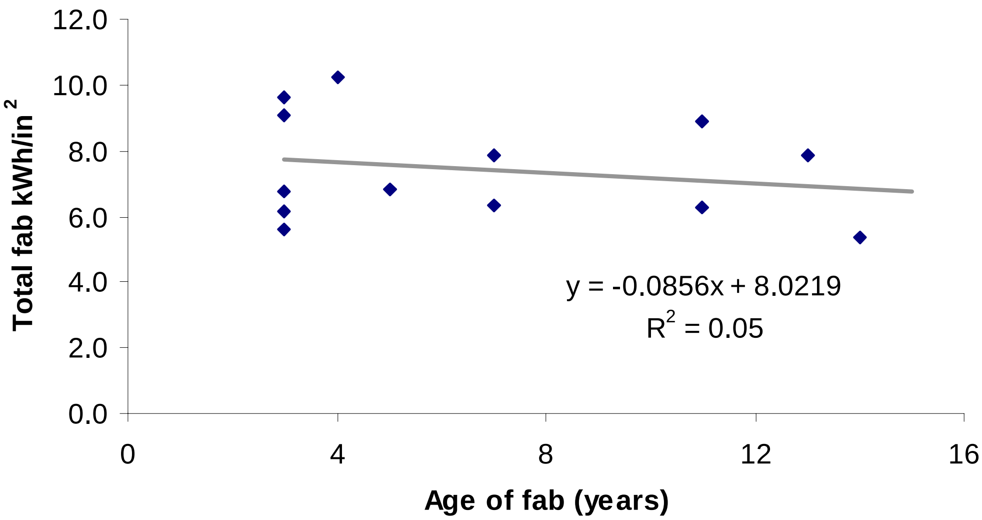

0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Chiller plant
kWh/unit of production
y = 0.0015x + 0.0052
R^2 = 0.2623
40
50
60
70
80
90
Average annual temperature (F)


0.06
0.05
0.04
0.03
0.02
0.01
0
Exhaust system kWh/unit of production
0.01
0.1
1
10
100
1000
Fab minimum class

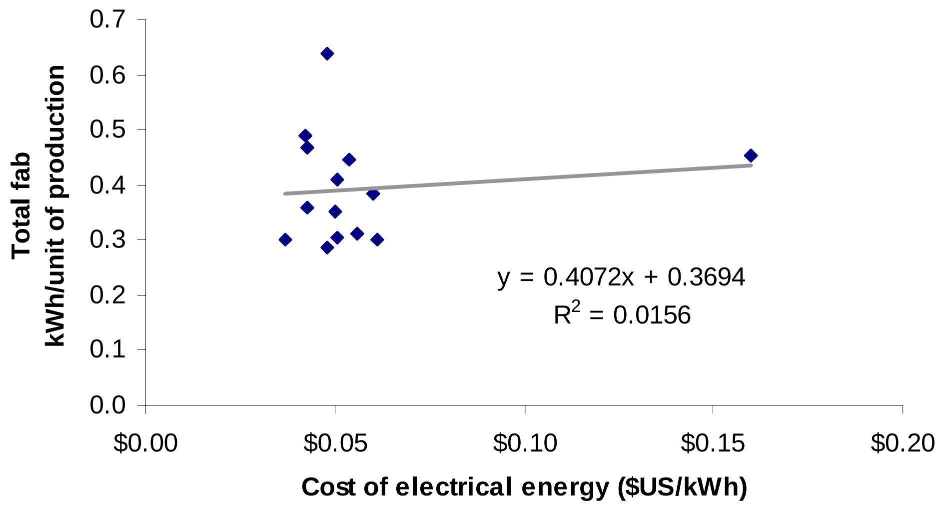

120
100
80
60
40
20
0
HEPA velocity (feet per minute)
0.01
0.1
1
10
100
1000
Fab minimum class

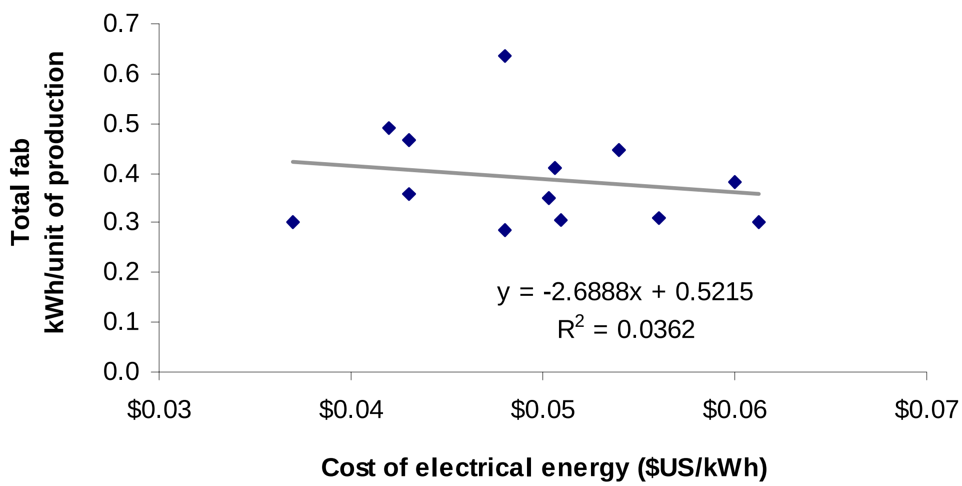


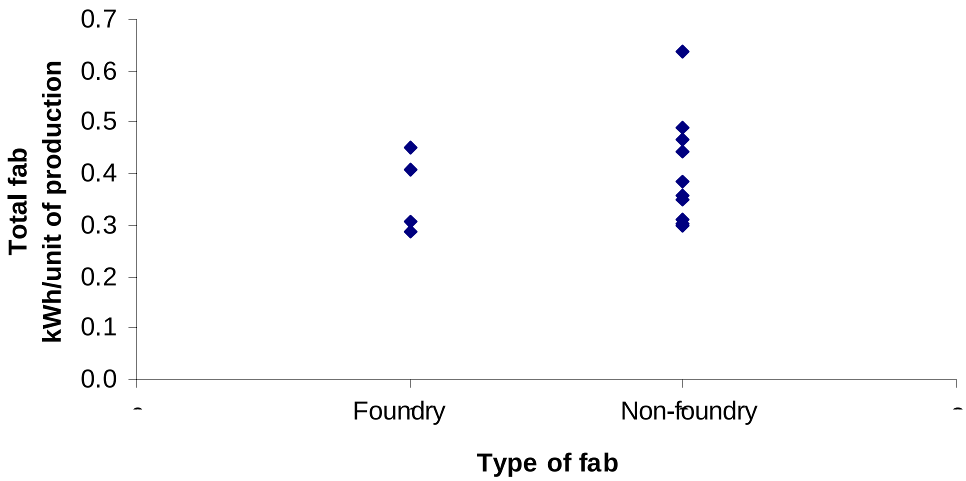
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Total fab kWh/in 2
y = 0.0088x + 6.8795
R2 = 0.0032
40
50
60
70
80
90
Average annual temperature (F)

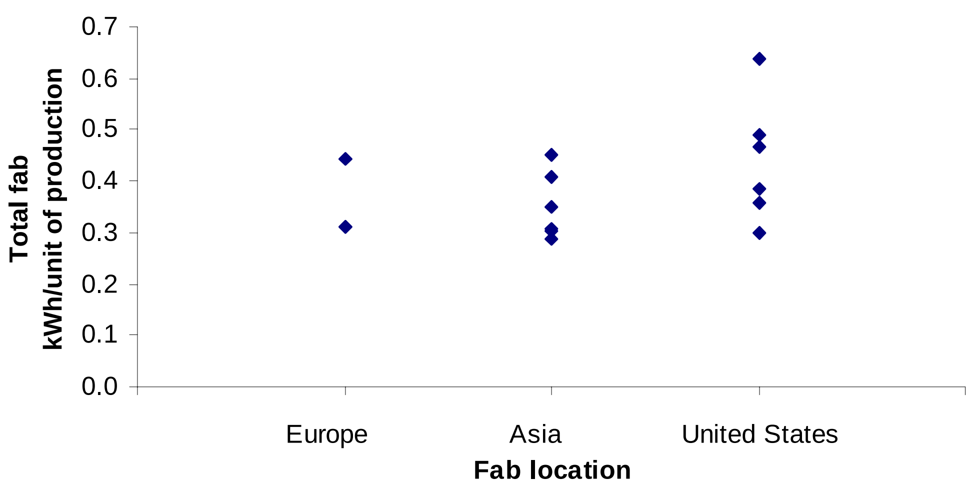


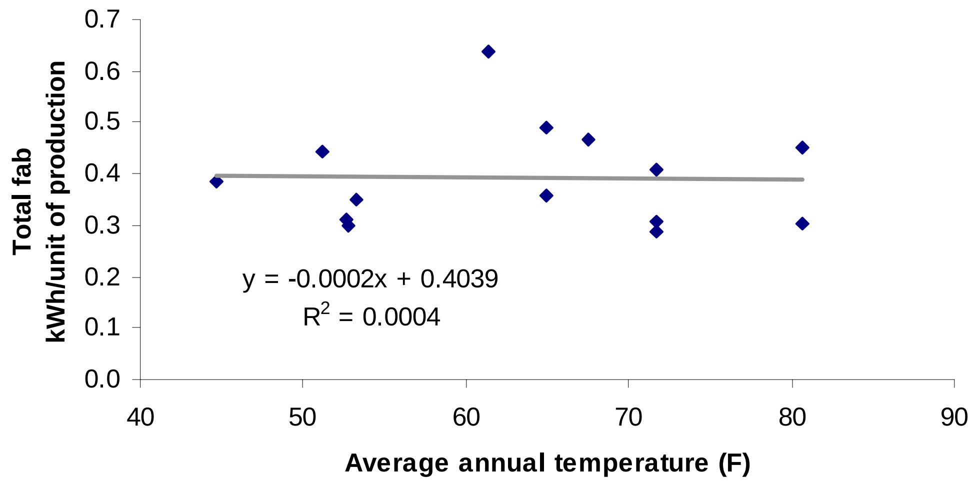
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Total fab kWh/in 2
y = -0.0856x + 8.0219
R2 = 0.05
0
4
8
12
16
Age of fab (years)


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Total fab
kWh/unit of production
y = 0.4072x + 0.3694
R2 = 0.0156
$0.00
$0.05
$0.10
$0.15
$0.20
Cost of electrical energy ($US/kWh)

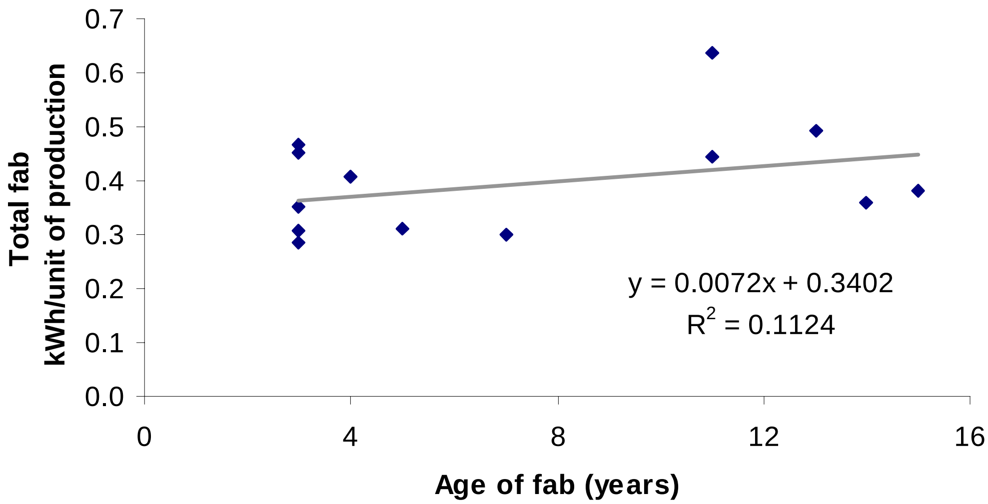

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Total fab
kWh/unit of production
y = -2.6888x + 0.5215
R2 = 0.0362
$0.03
$0.04
$0.05
$0.06
$0.07
Cost of electrical energy ($US/kWh)


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Total fab
kWh/unit of production
Foundry
Non-foundry
Type of fab

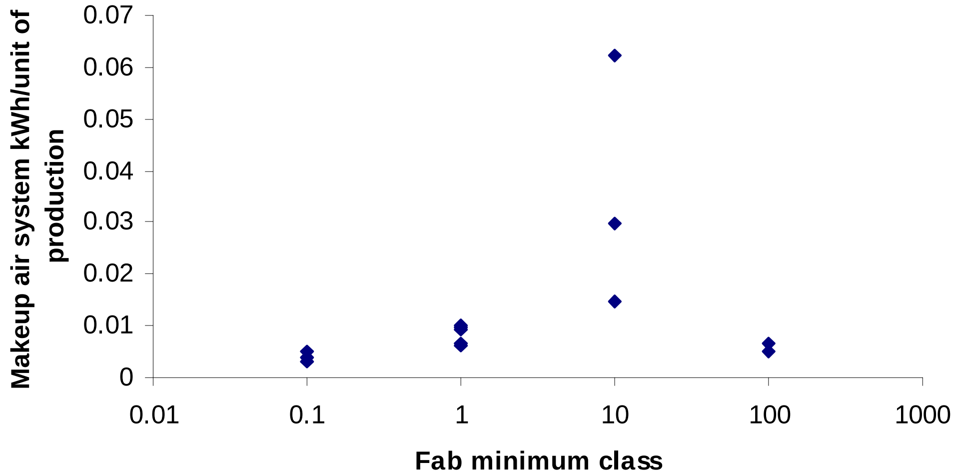

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Total fab
kWh/unit of production
Europe
Asia
United States
Fab location



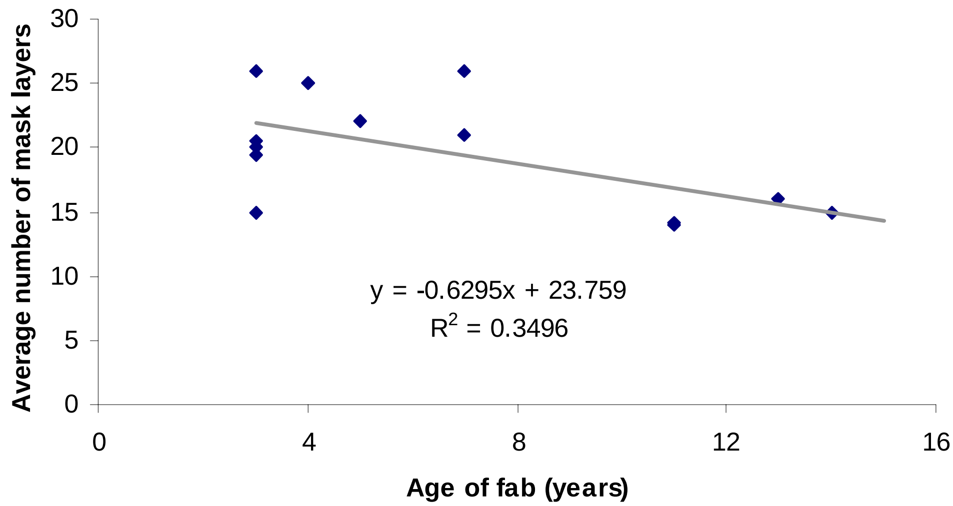
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Total fab
kWh/unit of production
y = -0.0002x + 0.4039
R2 = 0.0004
40
50
60
70
80
90
Average annual temperature (F)



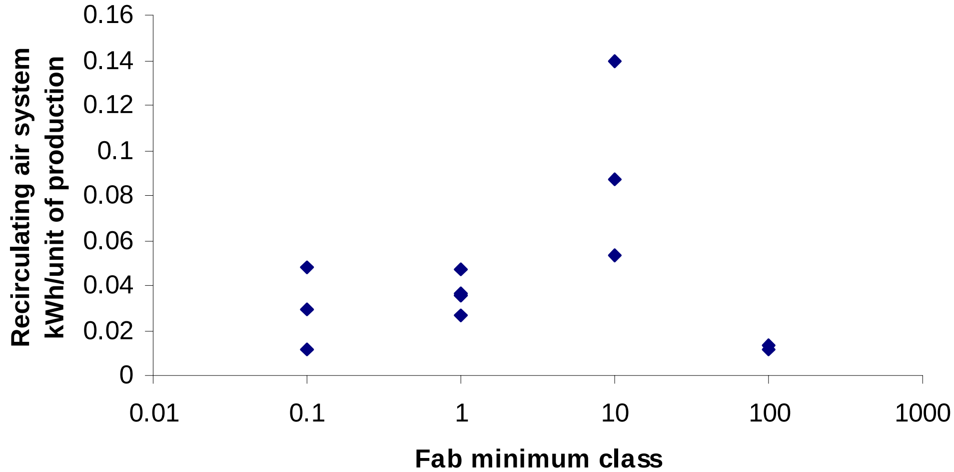
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Total fab
kWh/unit of production
y = 0.0072x + 0.3402
R2 = 0.1124
0
4
8
12
16
Age of fab (years)

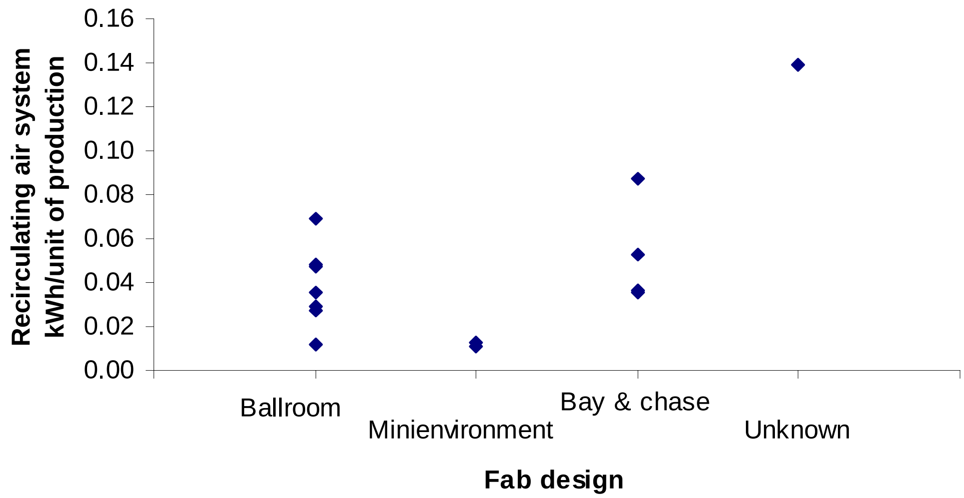


Makeup air system kWh/unit of production
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.01
0.1
1
10
100
1000
Fab minimum class



Average number of mask layers
30
25
20
15
10
5
0
0
4
8
12
16
Age of fab (years)
y = -0.6295x + 23.759
R2 = 0.3496


Recirculating air system
kWh/unit of production
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.01
0.1
1
10
100
1000
Fab minimum class


Recirculating air system
kWh/unit of production
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Ballroom
Minienvironment
Bay & chase
Unknown
Fab design

Target:

Electronics Industry

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