Energy Consumption of Personal Computer Workstations

Richard F. Szydlowski and William D. Chvála, Jr., Pacific Northwest Laboratory

A field study directly measured the electric demand of 189 personal computer workstations for 1-week intervals, and a survey recorded the connected equipment at 1,846 workstations in six buildings. Each separate workstation component (e.g., computer, monitor, printer, modem, and other peripheral) was individually monitored to obtain detailed electric demand profiles. Other analyses included comparison of nameplate power rating with measured power consumption and the energy savings potential and cost-effectiveness of a controller that automatically turns off computer workstation equipment during inactivity. An important outcome of the work is the development of a *standard* workstation demand profile and a technique for estimating a whole-building demand profile. Together, these provide a method for transferring this information to utility energy analysts, design engineers, building energy modelers, and others. A life-cycle cost analysis was used to determine the cost-effectiveness of three energy conservation measures: 1) energy awareness education, 2) retrofit power controller installation, and 3) purchase of energy-efficient PCs.

Introduction

The explosive growth of the information age has had a profound effect on the appearance of today's office. Although the telephone still remains an important part of the information exchange and processing system within an office, other electronic devices are now considered required equipment within this environment. This office automation equipment includes facsimile machines, photocopiers, personal computers, printers, modems, and other peripherals. A recent estimate of the installed base indicated that 42 million personal computers and 7.3 million printers are in place, consuming 18.2 billion kWh/yr—and this installed base is growing (Luhn 1992).

According to 1986 estimates, computers and other miscellaneous office equipment consumed 15% to 17% of the total energy in commercial buildings in the Pacific Northwest (DeLaHunt 1990). The energy impacts are even more substantial when the additional air-conditioning requirements attributable to equipment heat generation are considered.

Energy efficiency of personal computer workstation equipment has become a hot topic. Computer manufacturers agree that the sophisticated power conservation techniques built into the latest battery-operated laptop computers can be incorporated into the standard desktop computers, as soon as buyers are willing to pay a slightly higher cost for the energy savings features. The Environmental Protection Agency (EPA) Energy Star program is a positive step toward creating a market for more energy-efficient computer equipment by encouraging buyers to purchase equipment that meets energy conservation standards set by the EPA. The standards dictate that Energy Star computers and video display monitors have a power-saving mode that operates either at 80% of normal power or less than 30 W each during periods of inactivity. Over 70 computer equipment manufacturers have announced intentions to develop and market Energy Star-compliant equipment. A limited number are already on the market, with more product announcements expected.

Significant effort has been expended on engineering calculation, modeling, and indirect measurements based on whole-building "plug" loads, computer on-time (Tiller and Newsham 1993), and one-time measurements of electricity consumed by personal computer workstation equipment during idle operation (Tiller and Newsham 1993; Norford et al. 1988). However, no direct field measurements of personal computer workstation load profiles had ever been taken. Load profiles are time-series data that show the actual electric demand and consumption throughout a test period of one or more days. This information is necessary for the identification of cost-effective energy conservation strategies, for both retrofits to existing equipment and purchase specifications for new equipment.

In this paper, an extensive field study of computer workstation electric demand is described. The connected equipment at 1,846 personal computer workstations in six buildings at the Hanford Site, Richland, Washington, was surveyed during August 1990 through August 1992. The electric demand profiles of 189 personal computer workstations were directly measured. Each of the separate personal computer workstation components (e.g., computer, monitor, printer, modem, and other peripherals) was individually monitored to obtain detailed electric demand data for approximately l-week periods.

This paper details the methodology and equipment used in collecting field measurements and survey data. The resulting analysis of personal computer workstation electric demand and energy consumption is described. In addition, the paper documents how an electric power controller that automatically turns off a computer's monitor during keyboard/mouse inactivity was evaluated (in terms of energy savings potential and cost-effectiveness) as one energy conservation retrofit technology strategy.

To the best of our knowledge, this study is the first in which standard time-of-day electric demand profiles are developed from extensive direct field measurements of electric load profiles.

Scope

A *personal computer workstation* (PC workstation) is defined as a system assembled from a number of individual devices, including the computer, monitor (video display terminal), printer, external disk drive, external modem, plotter, and other peripheral equipment. Throughout the remainder of this paper, *computer* will refer to only the central processing unit (CPU), which does not include the monitor. A *personal computer* (PC) is defined as the computer plus monitor—without any other external peripheral equipment. Exceptions include computers with built-in monitors and workstations whose monitors are not powered separately and thus cannot be monitored separately. These definitions are necessary to uniquely identify the energy characteristics of a computer, monitor, PC (i.e., combined computer and monitor), and PC workstation (i.e., computer, monitor, and all peripheral equipment).

This study was conducted at the Hanford Site, a 560-mi^2 research installation near Richland, Washington, operated by four contractors for the U.S. Department of Energy. More than 15,000 employees conduct over 1,000 programs in environmental restoration and energy research at the Site. Six office buildings at the Site were chosen for investigation. The buildings vary in size from 20,440 to 203,375 ft^2, and their use varies from scientific and computer research to administrative.

Although all six buildings (1,846 PC workstations and 3,472 devices) were surveyed, field measurements were taken in only five of the six buildings. A representative sample of 189 PC workstations that contained 592 individual devices was selected for field measurements. Most network equipment (e.g., all file servers, local area network (LAN) equipment switches and drivers, and most network printers), as well as central mainframe and minicomputer systems, were not included.

Methods and Procedures

Field measurements for each of the 189 PC workstations used a 1-week monitoring period, with a time-series record (TSR) integration period of 30 minutes, providing the required detail for both workday and nonworkday demand profiles. No special instructions were given to the PC workstation users except to operate as usual. At the end of the week, data was downloaded to a portable computer in the field, and the data loggers were moved to the next workstations.

Field Data Collection

Four data acquisition systems, composed of a specially developed multiple-outlet monitor (MOM) and a 16-channel data logger designed to measure electric power, were used to conduct all the field measurements. The MOM was developed as a substitute multiple-outlet electric power strip that can separately monitor up to seven workstation devices. The data loggers used electric current transformers and potential transformers built into the MOM to sample the amperage and voltage and to conduct real-time calculation of true electric power for each of the seven outlets and the total workstation.

The data loggers are capable of recording more than 1 week of 30-minute TSRS in internal battery-backed random access memory (RAM), which allowed unattended operation during the test period. All the electric power measurements recorded are true power for both sinusoidal and nonsinusoidal voltage and current wave forms. This is important because the switching power supplies in most workstation equipment are nonlinear and dramatically distort the current waveform, with typical total harmonic distortion (THD) in the current waveform of greater than 100%.

In addition to the field measurements, a short informal office automation equipment survey was used to collect information about every workstation installed in each building. The following information was recorded for 1,846 PC workstations:

- types of electronic equipment present
- manufacturer and model of each
- nameplate ratings

- occupation of primary user
- nominal work-hours.

Data Processing

The raw TSR data was reduced into average 24-h demand profiles developed for workdays and nonworkdays. Workdays are normally Monday through Friday weekdays. Nonworkdays are weekends and holidays. These average-day demand profiles are useful summaries of the raw TSR data, which otherwise varies dramatically from hour to hour and day to day as workers' office hours vary due to meetings, business travel, and vacations.

The individual workstation demand profiles were summed to develop a measured building demand profile. Although the form of this measured profile was representative of the entire building's demand profile, the magnitude of the demand was low because only a subset of the installed PC workstations was monitored. Whole-building demand profiles were constructed using measured building demand profiles scaled on the basis of the number and type of installed workstations, as determined by the surveys.

The individual demand profiles are averages of multiple days, which typically include equipment that is on some days and off on others. Because each device can be only on or off, the maximum demand of the equipment will usually be higher than any of the average demand profile values. However, because most of the equipment was on for at least one TSR (30-minute integration time) during the field monitoring, each device's maximum load was determined by finding the maximum TSR during the test period.

Results

The results are based on one week of monitoring at each of the 189 locations, which included a total of 592 individual devices. Only 182 of the 189 monitored sites were included in the final analysis because 7 locations had incomplete data sets resulting from occupant interventions such as unplugging the data logger power during part of the monitoring period or unplugging part of the workstation equipment power from the MOM during an unknown part of the monitoring period.

Computer Classification

Table 1 shows a breakdown of the average operating load for the personal computer (i.e., CPU and monitor) configurations tested. The personal computers were categorized into one of four load classes. These load classes were based on natural groupings of measured load—realizing that a specific personal computer model can vary widely, depending on its configuration. Class II was the most common, identified 93% of the time in the survey. The largest workstation loads, Classes III and IV combined, were limited to 7%. The class percentages for the monitored sites are similar to the survey percentages, indicating that the monitored sites are a fair representation of the total population of PC workstations.

Table 1 also provides a component-based breakdown of the whole workstation in each load class, It shows the individual contributions to average electric demand of a variety of peripheral equipment commonly found as a part of a workstation. Peripherals generally contributed less than 20% to the total electric demand of a workstation—with the exception of the low-power Class I.

The penetration for each piece of peripheral equipment was determined by surveying the composition of all of the workstations in the six buildings surveyed. Thus, the penetration of 18% for impact printers for Class II workstations means that 18 out of 100 of these systems (as surveyed) had impact printers. The value of the average electric demand was calculated by averaging the metered data for all of a particular type of peripheral. The contribution to the total workstation electric demand of a particular peripheral is calculated by multiplying the peripheral's electric demand by the penetration.

Nameplate Ratings

In estimating the energy consumption characteristics of a piece of electronic office automation equipment, the only information that is usually available is the manufacturer's nameplate electric rating. The nameplates typically provide values of maximum amperage rating, often supplemented with voltage and wattage ratings, which can be used to calculate power consumption. However, our research has shown that nameplate ratings do not accurately represent the true magnitude of the energy consumption of a piece of equipment. This is not surprising because nameplate ratings indicate maximum equipment loading for safety purposes, not expected nominal energy consumption.

What fraction of the equipment's nameplate rating should be used when planning for a building's plug load? The answer is presented as a power derate, the fraction of nameplate power rating actually measured. Based on valid nameplate rating information, available on 118 of the 189 monitored PCs, the *standard* power derate was calculated as 0.231. This derate value indicates that the calculated nameplate wattages were more than four times greater than actual.

Although the power derate values are based on data for personal computers (i.e., computer and monitor),

Table 1. Personal Computer Workstation Load by Class

	Average Demand, W	*Standard* Workstation, W	Class I, W	Class II, W	Class III, W	Class IV, W
Load Class Range			0 to 75	75 to 175	175 to 250	250 to 350
Number of PCs Monitored		182	4	158	17	3
Personal Computer:						
CPU		85[(a)]	34	79	131	209
Monitor		60	0	61	70	80
Total CPU and Monitor		145	34	139	201	289
	Average Demand, W	**Peripheral Equipment Penetration, % of Workstations with Device**				
Peripherals:						
Impact Printer	13	17%	10%	18%	5%	0%
Laser Printer	80	25%	30%	24%	39%	40%
External Drive	22	13%	40%	12%	32%	0%
Modem	8	1%	0%	1%	3%	0%
Plotter	13	3%	0%	3%	8%	0%
Scanner	19	1%	7%	1%	0%	0%
Autocad	6	9%	0%	8%	24%	40%
Other PC Equip	26	7%	10%	7%	3%	0%
Total Peripherals, W		28	38	27	42	34
Total Workstation, W		173	72	166	243	323

(a) Electric demand given in watts except percentage figures as noted.

nonlinear power supplies are very similar for all electronic office equipment, and the power derates can be applied to the entire range of PC workstation equipment. The exception is electronic equipment that has a significant electric heater or motor load, such as a laser printer or copier during warmup or operation.

Workstation Demand Profiles

Application of the results specific to the five monitored buildings to other buildings requires the development of a normalized building demand profile for PC workstations. The first step was development of whole-building workstation demand profiles, based on field-measured electric demand data, analyzed as earlier described. These measured demand profiles were then normalized to the measured maximum load. The measured maximum load is calculated by summing the maximum load measured during the monitoring period for each device. This is equivalent to having all the equipment turned on simultaneously. The result is called the normalized building demand profile, or BDP for short. Figures 1 and 2 show the individual BDPs for workdays and nonworkdays.

Each workday and nonworkday BDP defines the demand profile for workstations during an average day. The demand values are the fraction of maximum demand. The maximum demand will occur only if all the workstation equipment is powered on at the same time. However, with a large number of users and workstations, diversity of operation results in 12% to 35% of the equipment demand being off, even during the middle of a workday.

A *standard* demand profile (SDP) for an office building was developed by using a weighted average of the BDPs from all five monitored buildings (see Figure 3). The weighting accounted for the number of workstations in each building. The workday *standard* demand profile has a baseload of 18% and peak load of 76% of the maximum load.

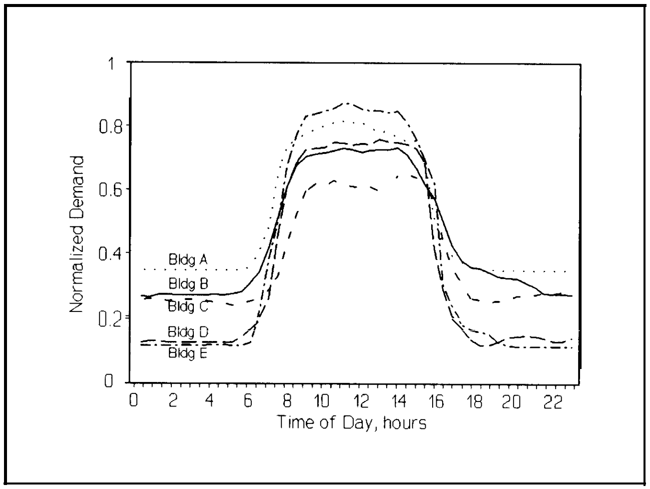

Figure 1. Workday Workstation Building Demand Profiles

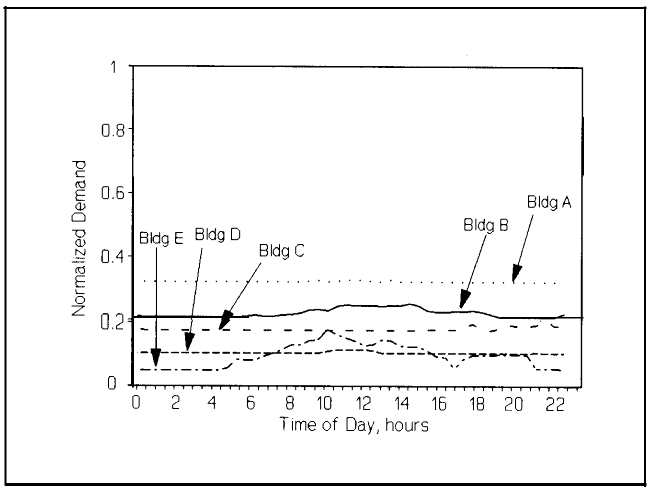

Figure 2. Nonworkday Workstation Building Demand Profiles

These demand profiles reflect building occupant impact on the demand and power consumption of office workstations. The baseload is attributable to equipment that is left on overnight. There is potential for energy savings by turning off some of this equipment. The peak load is less than 100% because of the diversity in equipment usage. Diversity examples include equipment that is rarely used or is not on because the staff are out of the office (vacation, sick leave, or travel) and/or practice energy conservation by manually turning off equipment when it is not being used.

The workday *standard* demand profile's nearly constant demand during regular office hours and nighttime allows for the workday *standard* demand profile to be accurately approximated as a simple "hat profile." The hat profile assumes an 18% nighttime baseload (17:30 to 08:00) and

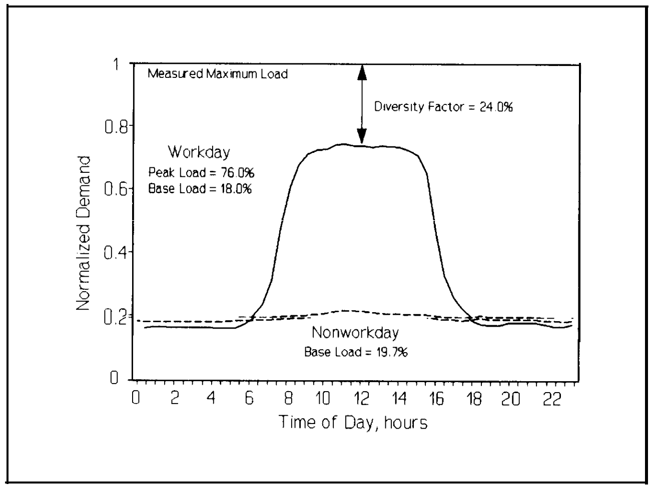

Figure 3. Workstation *Standard* Demand Profiles

a 76% daytime peak load (08:00 to 17:30). The nonworkday SDP can be simplified to a constant 21% value.

Personal Computer Demand Profiles

The workstation demand profiles previously presented included all PC workstation equipment—computer, monitor, printer, external disk drives, and so on. However, the PC workstations can be divided into two classes: single-user PCs (SU-PCs) and high-power multi-user PCs (MU-PCs). These two workstation classes have different use patterns. The MU-PCs are a special case because they are typically network resources (with distributed computing and data storage) and cannot be easily turned off during nonwork-hours. The MU-PC workstations represent only 11% of the total workstations, but most are on continuously.

The SU-PC and MU-PC workstation SDPs, including the overall average workstation SDP for comparison, are shown in Figure 4. The resulting SDP for SU-PCs has a baseload that decreased from 18% to 12% of the maximum load. This means that most of the SU-PC category is being turned off during nonwork-hours. The SU-PC SDP is very important because most energy conservation measures are targeted toward this category of computers and monitors, and the demand during nonwork-hours may be the principal target of potential energy savings measures.

PC Monitor Power Controller Evaluation

The best way to conserve energy is to turn off devices that are not being used. While screen savers blank the screen to save the triphosphors, they leave the monitor's internal elements warm and consuming the same amount of power

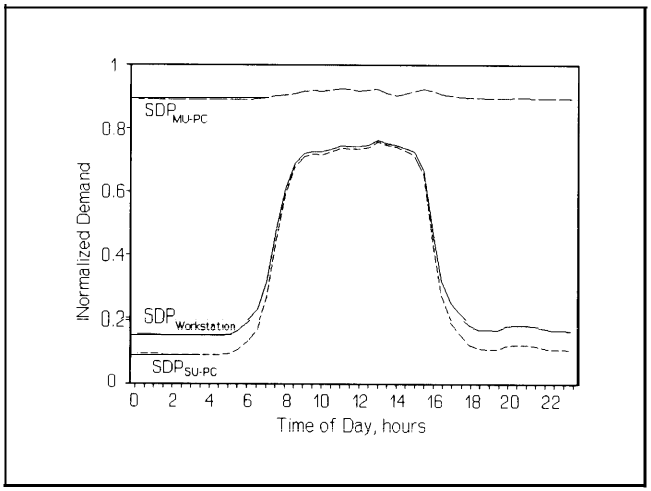

Figure 4. SU-PC and MU-PC Standard Demand Profiles

as when lit. Retrofit automatic power controllers operate differently, sensing keyboard activity and turning off the power to the monitor when no activity has been detected after a set period of time. Pressing any key will repower the monitor, returning the display to exactly where the user left off. The 10- to 20-second warmup time necessary to repower the monitor was generally acceptable, so long as the time-out period was long enough to prevent frequent interference during normal operation. Open software applications are not affected by the monitor power cycle.

Two monitor power controllers, both commercially available and designed for retrofit applications, were used for this concept evaluation. The controllers monitored keyboard and/or mouse activity and had a time-out period set to 20 minutes. Monitor power controllers were installed and measured on 11 workstations for at least 1 week each. The energy savings was calculated by estimating a demand profile for the same monitor during the same time with no power controller. This was accomplished by using computer (CPU) on-time as an indicator of when the monitor would have been on without the power controller. The difference between the two demand profiles indicated the consumption and demand savings.

Note that the results are dependent on the specific sample of PCs selected. Larger energy savings will result from selection of low-usage but high on-time PCs. This includes PCs that are left on overnight on workdays and continuously on nonworkdays. The sample selected was expected to demonstrate a very conservative energy savings because it included only computers that were manually turned off at night on workdays and all day on nonworkdays. All the energy savings was therefore limited to inactivity periods during work-hours.

The power consumption of monitors that are manually turned off during nonwork-hours was reduced 25% to 51%. Figure 5 shows the average normalized demand profile for the 11 monitors with power controllers. The average energy consumption reduction was 34%. The average peak demand reduction was 21%.

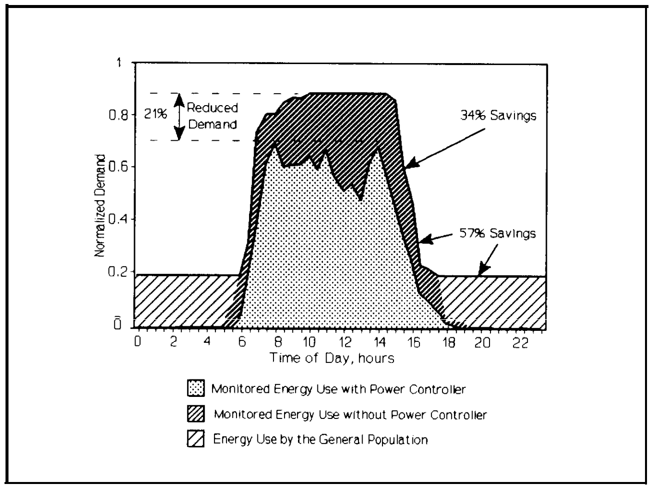

Figure 5. Monitor Controller Savings Extrapolated to the General Population of PCs

Extrapolation of this power controller test to the PC population requires the addition of an 18% baseload, which represents the average number of PCs left on during nonwork-hours, as defined by the SDP. The workday energy savings increased from 34% to 48%, and the addition of nonworkday energy savings results in an annual energy savings of 57%. This represents the power controller energy savings potential for the PC population.

Recent advances in automatic power controllers have resulted in more sophisticated devices. One commercial device has multiple, independently controlled outlets and is controlled by software configured by the user. This provides greater potential for energy savings because not only the monitor but other PC workstation equipment, including the computer itself (after saving all open software applications), can be controlled by the device.

Life Cycle Cost Analysis of Energy Savings

Although the proliferation of personal computer workstations and other office automation equipment has increased the demand for energy in office buildings, it also represents an area of potential energy savings through increased conservation and energy efficiency measures. Three energy conservation measures (ECMs) were evaluated: 1) implementation of an energy awareness program to educate PC workstation users to turn off PCs when not in use; 2) retrofit of existing monitors and computers with automatic power controllers; and 3) purchase of energy-efficient PCs as replacements on failure or obsolescence.

Three PC electric demand profiles were evaluated: 1) a $SDP_{SU\text{-}PC}$; 2) a high energy-use SU-PC, with a demand profile of 1.0 for workdays and 0.0 for nonworkdays (i.e., PCs normally on and not used during workday nonwork-hours [nighttime] and off during nonworkdays); and 3) a maximum energy-use SU-PC, with a demand profile that is continuously equal to 1.0 (i.e., PCs normally on and not used during both workday nonwork-hours [nighttime] and nonworkdays).

The energy savings estimates are for SU-PCs only. MU-PCs were not included because they are typically distributed system resources and cannot be easily removed from their LAN. The energy savings estimates also exclude the potential savings for peripheral equipment. Laser printers, which are 12% of the total PC workstation demand and 71% of the peripheral equipment demand (see Table 1), should be considered in future energy awareness and retrofit power controller programs. Although the power for laser printers can be controlled by retrofit power controllers, many of the laser printers are connected through a LAN and cannot be easily removed.

The cost-effectiveness of these energy savings measures is dependent on the local cost of energy. Electric rates at the Hanford Site are based on two sources. The City of Richland electric utility rate structure has a consumption charge of $0.02/kWh and demand charges of $4.64/kW on-peak (daytime) and $1.04/kW off-peak (night and weekend). Westinghouse Hanford Company (WHC) has a direct Bonneville Power Administration (BPA) contract for $0.055/kWh, with no direct demand charges. These electric rates are very low and not representative of most other areas of the United States. For comparison, the economic analysis includes a typical U.S. electric rate structure of $0.10/kWh consumption and $10/kW on-peak demand.

According to provisions of 10 CFR 436, federal agencies are required to analyze all potential energy investments using a life-cycle costing (LCC) methodology developed by the National Institute of Standards and Technology (NIST) (National Bureau of Standards 1987). The NIST LCC methodology proceeds by calculating all relevant costs of a project and discounting them to result in present dollars, then subtracting that sum from a similarly constructed LCC of a “no-action” baseline. This difference is called the net present value (NPV) of the action being considered. Actions are recommended for implementation if the NPV is positive and greater than the NPV of any competing actions. This methodology results in minimizing the LCC of energy services at a site.

Energy Awareness

Teaching energy conservation is the least expensive ECM, although possibly the most difficult in terms of effort required to produce the desired change over the long term. Studies have shown that while initial efforts at raising energy awareness are often successful, the modified behavior returns to its original patterns within a short time. The NRC study’s energy awareness test (Tiller and Newsham 1993) experienced an average 14% energy savings over an 8-week period. The savings were higher at the start of the test period, but they diminished to approximately zero at the end as users gradually returned to old PC usage habits. For an education program to work, the involved parties must work hard for an extended period to cause a permanent change in habits. To achieve and maintain a high participation rate at the Hanford Site (15,000 employees and 9,239 PCs), the energy awareness program was assumed to require a staff of two. The assumed program cost was $15/PC/yr.

This ECM assumes that PC users will become actively involved in reducing the energy consumption of their PC workstations by turning off all computers and monitors when not in use. Based on the energy savings determined in our evaluation of PC monitor controllers (see Figure 5), the savings for monitors were assumed to be 21% demand and 57% consumption during workdays and 100% consumption and demand during nonworkdays. Users were not expected to turn off their computers (CPUs) during work-hours because of the inconvenience of saving open software applications and rebooting. There is 0% computer energy savings during work-hours. However, users were assumed to turn off computers during nonwork-hours.

A realistic energy savings was calculated by derating the level of participation during the various portions of the work week. The PC user participation assumed was 20% during workhours, 80% during nonwork-hours of workdays, and 100% during nonworkdays. The level of participation was assumed to be constant over time based on an effective and continuous energy awareness campaign.

Retrofit Power Controllers

The large inventory of existing PC workstation equipment can be made more energy-efficient through retrofit of automatic power controllers. Unlike the monitor-only power controllers evaluated in the previous section, this economic analysis is based on commercially available power controllers that regulate both the monitor and computer. The power controller devices will realize a savings equal to the energy awareness campaign at 100% participation, plus the savings from turning off the computer during work-hours. Although other PC workstation devices could also be controlled by the power controller, this scenario assumes control of only SU-PC monitors and computers.

In large quantities, the retrofit power controllers can be purchased for $50 to $150 each. However, implementation of the retrofit power controllers must include purchase, distribution, training, and repair services, which will add approximately $25 per PC. The economic analysis assumed $125 per PC based on a device that can control both computer and monitor. A $5/yr operations and maintenance (O&M) cost was used to repair or replace a 5% power controller equipment failure rate.

Energy-Efficient Equipment Purchase

Energy-efficiency technologies, similar to those already available in laptop portable PCs, can be designed into new PC workstation equipment. The workstation equipment included in the EPA's new Energy Star program is required to have a low-power state that is at least an 80% reduction from normal idle power, or less than 30 W. The equipment will sense user inactivity and automatically initiate and recover from the low-power, or sleep, state.

Energy-efficient equipment continues to consume a reduced power demand during periods of inactivity. The energy and cost savings for energy-efficient equipment are less than for the retrofit power controllers because the power controllers turn power off to the equipment instead of just reducing demand. However, built-in energy saving features should cost much less and should be seamlessly integrated into the personal computer operation, resulting in greater user participation than for the retrofit power controllers.

Firm data on the incremental cost of new energy-efficient PC equipment is unavailable. Because of pressure from large buyers (state and federal agencies) specifying energy-efficient PCs in new purchases and competing products, the incremental cost is expected to be small. The assumed incremental cost was $100 per PC (computer and monitor). Until the energy-efficient PC technology becomes widespread, organizations that currently purchase low-cost clone PCs will have an incremental cost that includes switching to more expensive namebrand PCs. In this case, the incremental cost for energy-efficient PCs will be much more.

Economic Analysis

The implementation cost, energy and demand savings, cost savings, and NPV for typical U.S. electric rates are summarized in Table 2. The LCC analysis is based on a 5-yr equipment life with no salvage value. All the cost analysis results are expressed in terms of cost per PC. A summary of ECM recommendations, based on LCC analyses similar to that shown in Table 2 for all three electric rates, is presented in Table 3. The electric utility perspective may differ because of avoided generation and distribution costs that are not included in this customer perspective evaluation.

The LCC analysis recommends "no-action" for single-user PCs that are operated according to the measured demand profile ($SDP_{SU\text{-}PC}$). The NPV is negative for all three ECMs and all three electric rates. At the assumed costs and measured demand profile for the Hanford Site, the lowest-cost energy conservation option is to do nothing.

This is counter to popular opinion regarding the value of PC energy conservation. In fact, the costs of the ECMs would have to be dramatically lower to be recommended. For Richland electric rates, the costs could not exceed $1/PC/yr for the energy awareness program, $19 capital and no annual O&M for the retrofit power controller, and $15 incremental cost for the purchase of new energy-efficient PCs. Under Westinghouse electric rates, the costs could not exceed $3, $39 and no O&M cost, and $31. And for the typical U.S. electric rates, the costs could not exceed $5, $80 and no O&M cost, and $64. The low electric rates at the Hanford Site make ECMs for PCs unattractive at this time.

Selective application of the ECMs will optimize the investment. Targeting high-energy-use PCs results in the energy awareness program for Westinghouse and all three ECMs for the typical U.S. electric rates becoming recommended actions. Targeting the maximum energy-use PCs results in all ECMs except the power controller retrofit for Richland rates becoming recommended actions. Selective application of the power controllers and energy-efficient PCs will require a low-cost method of identifying high energy-consumption PCs. For PCs connected to LANs, software could be developed that uses the LAN to identify and record PCs that are actively connected during nonwork-hours. A simple survey of user operation may identify high energy-consumption PCs not connected to a LAN.

The actual savings for the energy awareness program will be less, with actual participation dependent on the strength of the program. A less intensive, and perhaps more realistic, energy awareness program that advocates turning off only PCs that are on during nonwork-hours will capture 44% of the maximum cost savings while targeting only 12% of the total number of PCs.

The actual savings for the energy-efficient equipment may be greater because an 80% power reduction is the minimum required for the Energy Star program. A less intensive, and perhaps more realistic, program that limits

Table 2. Life-Cycle Cost Analysis per PC for Typical U.S. Electric Rates

Energy Savings Measure	Installed Cost (1993 $)	Annual O&M Cost (1993 $)	Annual Energy Savings (kWh)	Annual Demand Savings (W-mo) Peak	Off-Peak	Annual Energy Savings (1993 $)	Annual Demand Savings (1993 $)	Simple Payback (years)	Net Present Value (1993 $)
***Standard* Single-User PC (SDP $_{SU-PC}$, 341 kWh/yr):**									
Energy Awareness[(a)]	0	15	60	2	n/a	5.97	0.22	2.4	-45
Power Controller	125	5	188	23	n/a	18.77	2.71	6.1	-68
Energy Star[(b)]	100	0	150	18	n/a	15.02	2.17	5.8	-36
High Energy-Use PC (870 kWh/yr):									
Energy Awareness	0	15	210	3	n/a	21.00	0.30	0.7	11★
Power Controller	125	5	639	30	n/a	63.86	3.65	1.9	103★
Energy Star	100	0	511	24	n/a	51.09	2.92	1.9	101★
Maximum Energy-Use PC (1270 kWh/yr):									
Energy Awareness	0	15	610	3	n/a	61.02	0.30	0.2	160★
Power Controller	125	5	1039	30	n/a	103.88	3.65	1.2	252★
Energy Star	100	0	831	24	n/a	83.10	2.92	1.2	220★

(a) Assumed participation: 20% during workhours, 80% during nonwork-hours on workdays, and 100% on nonworkdays. Actual savings will be less because participation will normally decrease with time.
(b) Actual savings will be greater because an 80% power reduction is the minimum required for the Energy Star Program.
★ Star indicates recommended ECM.

Table 3. Energy Conservation Measure Recommendations for Single-User PCs

	***Standard* PCs (341 kWh/yr, 100% of PCs)**			**High Energy Use PCs (870 kWh/yr, 12% of PCs)**			**Maximum Energy Use PCs (1270 kWh/yr, 12% of PCs)**		
Energy Conservation Measure	**Richland Rates**	**WHC Rates**	**Typical US Rates**	**Richland Rates**	**WHC Rates**	**Typical US Rates**	**Richland Rates**	**WHC Rates**	**Typical US Rates**
Energy Awareness						★	★	★	★
Power Controller						★		★	★
Energy Star PCs					★	★	★	★	★

★ Star indicates recommended action.

purchase of energy-efficient equipment to PCs that are on during nonwork-hours will capture 44% of the maximum cost savings while targeting only 12% of the total number of PCs.

Conclusions

Field measurement of the electric demand of 189 personal computer workstations, together with surveys of installed equipment at 1,846 locations in six buildings, have provided the real-world data necessary to gain insights into the behavior and impacts of personal computer workstations.

Detailed data was collected for each separate workstation component (e.g., computer, monitor, printer, modem, and other peripherals). This information was summarized as *standard* workstation and *standard* PC demand profiles, for both workday and nonworkday time periods. Development of these standard conditions allows improved estimation of PC workstation demand and aids in managing the overall energy flows for other buildings.

Although the electric demand varies between and within computer models, 93% of the PC workstations surveyed were in a load class of 75 to 175 W. The *standard* PC had a demand of 144 W, and the *standard* workstation had a demand of 173 W. The peripheral equipment, such as printers and modems, accounted for only 16% of the overall workstation demand. This information indicates that energy conservation measures should target the computers (50% of total) and monitors (35% of total) first. Laser printers, which account for only 12% of total workstation demand, may also be important because they are typically powered on 24 h/day.

The comparison of nameplate ratings with measurements indicated that direct use of nameplate electric ratings will result in an overestimated demand. Use of a *standard* power derate of 0.23 multiplied by the rated values allows correction of the nameplate ratings.

The *standard* workstation demand profile provides a good estimate of the demand on a building's plug load attributable to all the PC workstation equipment. The *standard* PC demand profile works similarly. However, the SU-PC demand profile differs significantly from the MU-PC demand profile. Most users (approximately 93%) regularly turn off the SU-PCs during nonwork-hours. Most MU-PCS are left on continuously because they are a network resource. This has serious implications for ECM economics because the calculated energy savings potential for an SU-PC is significantly less for the SU-PC demand profile than it is for the workstation SDP.

Power controllers on monitors provided a 21% demand savings and 57% consumption savings. Energy consumption savings during work-hours was only 40% of the overall savings, indicating that the main energy conservation potential is for computers that are on during nonwork-hours. User acceptance of the monitor power controller was good. Although power controllers on computers were not tested, similar savings would be expected from application of an appropriate power controller and software to automatically save and retrieve open applications.

The LCC analysis for single-user PC energy conservation measures recommended "no action" for PCs that are operated according to the measured demand profile. In fact, the threshold costs for positive NPV of the ECMs are dramatically lower than the assumptions used in the previous section. When the incremental cost of energy-efficient PCs drops below $64 (at typical U.S. electric rates), this ECM is cost-effective. However, for the Hanford Site, the incremental cost must be less than $31 or $15, depending on the serving utility.

Many energy efficient computer equipment products are being announced or are already on the market. Pressure from large governmental and corporate buyers who require energy-efficient PCs, combined with trickle down power controller technology, will continue to lower the incremental cost of this equipment. Therefore, energy-efficient PCs will likely become the standard within a few years.

Acknowledgments

The study on which this paper is based was conducted by Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy (DOE) In-House Energy Management (IHEM) program and the Hanford Energy Management Committee (HEMC). The Pacific Northwest Laboratory is operated by Battelle Memorial Institute for DOE under Contract DE-AC06-76RLO 1830.

The authors gratefully acknowledge the assistance of John Schmelzer (PNL) for developing the multiple-outlet monitors and keeping the field data acquisition equipment operating; Patrick O'Neill and Michele Friedrich (PNL) for assistance in project development and data analysis; and Guy Newsham (Institute for Research in Construction, National Research Council, Canada) and Mary Ann Piette (Lawrence Berkeley Laboratory) for their review and comments.

References

10 CFR 436. 1992. U.S. Department of Energy, "Federal Energy Management and Planning Programs." *U.S. Code of Federal Regulations.*

DeLaHunt, M. J. 1990. "Trends in Electricity Consumption Due to Computers and Miscellaneous Equipment (CME) in Office Buildings." In *Proceedings of the ACEEE 1990 Summer Study on Energy Efficiency in Buildings,* Volume 3, pp. 3.67-3.75. American Council for an Energy-Efficient Economy, Washington, D.C.

Luhn, R. 1992. "Making PCs Environmentally Correct." *PC World*, June 1992, p. 112.

National Bureau of Standards (NBS). 1987. Life-cycle *Costing Manual for the Federal Energy Management Program.* NBS Handbook 135, U.S. Government Printing Office, Washington, D.C.

Norford, L. K., A. Rabl, J. Harris, and J. Roturier. *1988*. "The Sum of Megabytes Equals Gigawatts: Energy Consumption and Efficiency of Office PCs and Related Equipment." In *Proceedings of the ACEEE 1988 Summer Study on Energy Efficiency in Buildings*, Volume 3, pp. 3.181-3.196 American Council for an Energy-Efficient Economy, Washington, D.C.

Tiller, D. K., and G. R. Newsham. 1993. *Desktop Computers and Energy Consumption: A Study of Current Practice and Potential Energy Savings.* CEA 9101 U 829, Canadian Electrical Association, Montreal, Quebec, Canada.