WHOLE-CAMPUS PERFORMANCE ANALYSIS METHODS: EARLY RESULTS FROM STUDIES AT THE PRINCETON CAMPUS

J. Haberl, S. Englander, C. Reynolds,
Center For Energy and Environmental Studies
Princeton University

M. McKay, T.Nyquist
Facilities Engineering Department
Princeton University

ABSTRACT

The Princeton University Campus provides an excellent opportunity for evaluating energy data analysis techniques that use historical energy consumption data for the entire campus to target conservation opportunities. The Princeton Campus is comprised of approximately 150 buildings with a total conditioned floor area exceeding 6.2 million square feet. The annual utility bills total $7.2 million.

In this paper we present early results from efforts to improve the ability of campus administrators to make better decisions on energy-related issues by assembling a normalized energy consumption index that facilitates year-to-year comparisons of energy use. Our procedure combines plant operational data and utility consumption data with weather data and campus growth information. Utility consumption is normalized for varying weather conditions using PRISM, the Princeton Scorekeeping method, and then adjusted for conditioned floor area.

INTRODUCTION

The Princeton Campus. The 150+ buildings that comprise the Princeton University Campus, located in central New Jersey, are a diverse set of buildings ranging from dormitories and high-rise housing to historical buildings (built in 1756) and modern laboratories (1980's vintage). Figure 1 is a plan view of the Princeton Campus. The design of the campus can be described as centrally oriented and is served by a common utility distribution service.

The utilities provided to the buildings on campus include: electricity, steam, chilled water, and potable water. Natural gas (interruptible) and fuel oil are purchased from local suppliers. Electricity is purchased from a local utility supplier and redistributed from two campus substations. In 1988 the physical plant purchased 79,200 MWh (million watt-hours) of electricity and generated 675.1 Mlb (million pounds) of steam and 14.0 Mton-hr (million ton-hrs) of chilled water to provide services for the buildings on campus. Utility costs in 1988 totaled $7,237,000 of which $1,419,000 represented electric demand charges, $3,189,000 represented electricity usage and $2,629,000 was spent generating steam (consuming natural gas or fuel oil).

Figure 2 shows the historical campus growth from 1756 to 1988. Since 1960 the campus has doubled in size, adding about 3 million square feet for a current total of 6.2 million square feet. In 1988, 5.4 million square feet of the Campus were heated by steam from the central plant, 5.4 million square feet received electricity from the campus electrical distribution system and 2.8 million square feet were cooled with chilled water produced by the physical plant.

TYPICAL PROBLEMS FACED BY CAMPUS ENERGY DECISION MAKERS

We have found that campus operators have a need for concise, timely energy information. Current trends in energy management that rely on increased monitoring of building energy usage may not be cost effective for all buildings and often require constant attention by building personnel. Today's campus operators find themselves face-to-face with complex information management decisions that place additional demands on their valuable time. These same operators struggle with commissioning and re-commissioning their buildings, lack the resources to constantly calibrate sensors, upgrade software and trouble-shoot complex electronic monitoring and control equipment. They are also finding it increasingly difficult to fill highly skilled technical positions from a shrinking labor pool.

Facility administrators face information-based barriers as well. For example, year-to-year comparisons of energy consumption should be adjusted for varying weather conditions and for additions to the conditioned floor area. Such annual indices require weather-normalization and an adjustment for square footage of conditioned area for each major energy fuel being consumed. For the Princeton campus this meant one index each for electricity, steam production (fuel oil and/or natural gas consumption) and chilled water production (steam and/or electricity consumption). Such complex indices require the merging of data from several sources, as shown in Table 1. Collating 10 years of these data required retrieving records from archived storage, translating engineering units and adjusting for differences in accounting methods.

WEATHER NORMALIZED ENERGY USAGE

With the goal of improving the ability of the Campus administrators to track year-to-year energy consumption, despite varying weather conditions and continuous campus growth, we chose a two-step procedure: 1) model the temperature dependence with PRISM - the Princeton Scorekeeping Method, a three-parameter, steady-state model (Fels 1986), then 2) adjust the Normalized Annual Consumption (NAC) by dividing by the appropriate conditioned area. These two steps result in an energy consumption intensity index (W/ft^2 for each major consumption category. The value of such indices has been previously reported on by MacDonald (1988).

PRISM regresses energy consumption against

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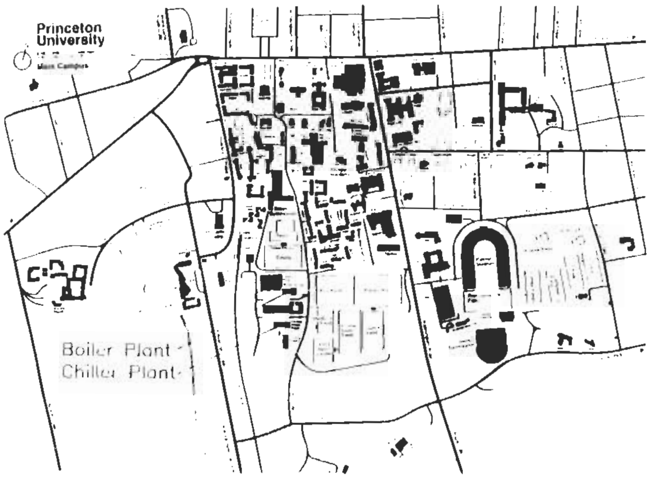

FIGURE 1 - Princeton University campus in plan view. The Boiler Plant and Chiller Plant are located adjacent to Poe Field as shown. Steam, electricity, chilled water, and natural gas are provided to campus buildings through an underground distribution system.

heating or cooling degree days (taken at the temperature which gives the best fit) and includes thorough goodness-of-fit statistics. For either heating or cooling data, the model yields a slope (fuel-use/degree-day), base-level consumption (fuel-use/day) and a balance point temperature. In order to calculate a total normalized energy index for the entire campus it was necessary to analyze chilled water production, steam production and electricity use separately.

Chilled Water Production. The monthly chilled water production for the period April 1977 through March 1989 is shown in Figure 3 and Figure 4 plotted against the monthly average temperature. PRISM parameters (for the period July 1987 to June 1988, also listed in Table 2) are shown. A PRISM Cooling only (CO) analysis of the chilled water production indicates that 72% of the chilled water production is cooling-related and 28% can be considered non-cooling dependent. PRISM also indicates that the chilled water production is well described (i.e., $R^2 = 0.97 > 0.70$, and $CV(NAC) = 0.03 < 0.07$) using the reliability criteria established by Reynolds and Fels (1988) for residential buildings. NAC, the Normalized Annual Consumption, is defined as the base-level consumption plus the weather-related consumption. It is an annual index of weather-adjusted energy use. R^2 is the indicator of the goodness-of-fit. CV(NAC) is the percent standard error of the NAC.

Next, sliding PRISM CO was applied to the chilled water production as shown in Figure 5. Sliding PRISM CO is PRISM CO applied in 12-month increments, sliding forward the estimation period one billing interval (usually one month) at a time. Standard errors are shown as dotted lines. Sliding PRISM CO clearly shows us several features of interest, namely, a 36% decline in the NAC from 1978 to 1982 (related to campus-wide indoor temperature policy and improved scheduling of air-handling units), a relatively flat period from 1982 to 1985 (with the exception of the rise in

ITEM:	SOURCE:
Monthly Oil Usage From:	Boiler Logbooks, Engineering, Suppliers
Monthly Electricity Usage From:	Business Office & Engineering
Monthly Steam Production From:	Boiler Logbooks & Engineering
Monthly Chilled Water Production From:	Chiller Logbooks & Engineering
Monthly Water Usage From:	Boiler & Chiller Logbooks, Engineering
Campus Square Footage From:	Planning, Engineering, Housing
Dates of Construction From:	Planning, Engineering, Housing, Site Insp.
Electricity Cost Information From:	Business Office, Engineering, Suppliers
Oil Cost Information From:	Boiler Plant, Engineering, Suppliers
Water Cost Information From:	Business Office, Engineering, Suppliers
Weather Data From:	Boiler Plant & N.W.S.
Schedule Information From:	Security Office, Grounds Office, Walk-Thru

NOTES: The 10+ years of information required to publish this paper took about 4 person-months to assemble. Significant portions of the historical records were extracted from the previous work performed by Rabl et al. (1986).

TABLE 1 - This table lists the information required to calculate whole-campus energy indices and the source(s) required. For example, calculating weather-normalized annual steam usage, adjusted for conditioned area for the entire campus, required merging information from the Boiler Plant, the Business Office, local fuel suppliers, the Facilities Engineering Office, the Planning Department, and the Housing Department.

cooling-related load during 1982 and 1983), and a significant 47% rise in chilled water production from 1985 to the present. The 1985 to 1988 rise in production appears to be due to two factors: an increase in the cooling load during 1985 and 1986 (certain laboratory buildings were brought on-line) and an increase in the base-level load from 1986 to 1988 (increased year-around cooling).

Steam Production. Total campus monthly steam production for the period April 1978 to March 1989 is shown in Figure 6 and Figure 7 plotted against average monthly temperature. In Figure 7 steam consumed by steam-turbine chillers in the chilled water plant and non-cooling steam (i.e., steam consumed for heating and other purposes), inferred by subtracting sub-metered steam for cooling from the total steam, are displayed against the average ambient monthly temperature together with parameters estimated from the PRISM heating-only (HO) (the solid line) and PRISM cooling-only (CO) (the dashed line) models.

A sliding PRISM analysis was performed on both the steam used by the steam-driven chillers and the steam used for heating (the non-cooling steam). Figure 8 displays the sliding Normalized

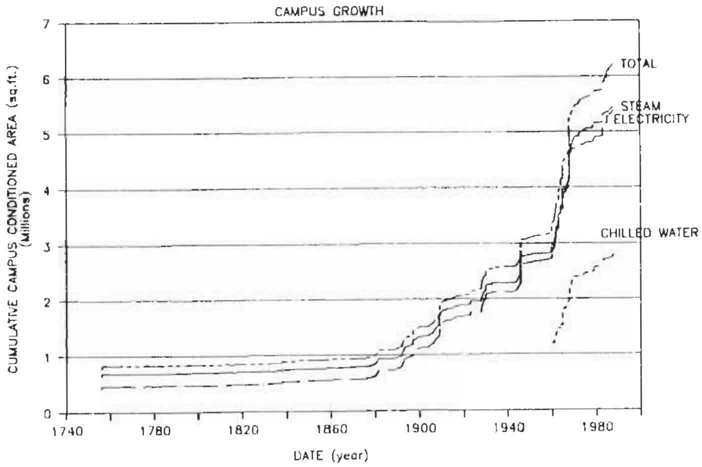

FIGURE 2 - This figure displays the campus growth from 1756 to 1988. Square footage is shown for all buildings (TOTAL), those buildings receiving steam from the central plant (STEAM), buildings receiving chilled water (CHILLED WATER), and buildings receiving electricity from one of two campus sub-stations (ELECTRICITY). Data for buildings that did not contain a construction date were added to the beginning of the data file used to construct this figure, hence the initial 780,000 ft^2. In actuality, in 1756 the campus consisted of two primary buildings, totaling 56,000 ft^2.

Annual Consumption for cooling steam (NAC - COOLING), the sliding NAC for heating steam (NAC - HEATING), and the sliding NAC for cooling steam plus heating steam (NAC - TOTAL). In this fashion the historical total steam production for the campus is represented by six parameters, namely, a heating-slope for non-cooling steam, a cooling-slope for cooling steam, and reference temperatures and base-levels for heating and cooling steam. PRISM also allows us to determine proportions of the steam used for heating, cooling or base-level purposes (The PRISM parameters for the period July 1987 through June 1988 are listed in Table 2).

For example, during the period July 1987 to June 1988, the PRISM CO analysis shows that 73% of the total annual cooling steam was cooling-related and the remaining 27% was non-cooling related (base-level) and is well determined (i.e., R^2 = 0.94, CV(NAC) = 0.08). The sliding PRISM CO analysis, applied to the cooling steam consumption (Figure 8), shows a relatively flat consumption from 1979 to 1982, a 50% increase in consumption from 1982 to 1987, and a 28% dip in consumption in 1987 with a corresponding return to previous consumption levels.

The PRISM heating only (HO) model applied to heating steam (i.e., non-cooling steam) indicates that 62% of the total is heating-related with 38% non-heating-related (base-level) use and is again well described (i.e., R^2 = 0.98, CV(NAC) = 0.07). Sliding PRISM HO applied to the non-cooling steam (Figure 8) indicates a slight 8% decrease in non-cooling steam from 1979 to 1982 followed by a 22% rise in steam usage from 1982 to 1988.

CAMPUS ENERGY USAGE PARAMETERS

Non-Cooling Steam Production
(July 1987 through June 1988)

1. slope (Mlb/F-day) = 0.068 (0.006)
2. base level (Mlb/day) = 0.57 (0.08)
3. balance point temperature (F) = 65.4 (2.6)
   R^2 = 0.979
   NAC (Mlb) = 548 (15)
   heating part (Mlb) = 341 (25)

Cooling Steam Production

4. slope (Mlb/F-day) = 0.036 (0.007)
5. base level (Mlb/day) = 0.10 (0.05)
6. balance point temperature (F) = 56.0 (4.3)
   R^2 = 0.944
   NAC (Mlb) = 131 (10)
   cooling part (Mlb) = 95 (13)

Chilled Water Production

7. slope (ton-hr/F-day) = 3.46 (0.34)
8. base level (ton-hr/day) = 10.98 (2.01)
9. balance point temperature (F) = 54.3 (2.1)
   R^2 = 0.986
   NAC (Mton-hr) = 14.18 (0.47)
   cooling part (Mton-hr) = 10.17 (0.62)

Electricity Consumption

10. average (MWh/day) = 216.4 (3.6)

NOTES: The PRISM CO and HO parameters are listed along with their relative standard error (coefficient of variation). For example, parameter 7, the chilled water slope, is 3.46 ton-h/F-day and has a coefficient of variation of 0.34.

TABLE 2 - Here we list the 9 PRISM parameters and 1 non-PRISM parameter that describe the temperature and non-temperature dependence of steam and chilled water and non-temperature electricity use.

Total weather-normalized steam production, inferred by adding the NAC from PRISM HO for non-cooling steam and the NAC from PRISM CO for cooling steam, indicates a 9% decrease in steam consumption during 1979 through 1981, a 27% increase in steam production during 1981 through 1987 with a slight 6% dip in consumption in 1987 (caused mostly by a decrease in cooling-related steam consumption) followed by a 7% increase in consumption from 1987 to 1988.

Electricity Consumption. Metered electricity consumption (MWh) and demand (MW) for the campus are shown in Figure 9. Monthly electricity use (non-weather-adjusted) for the campus has risen from an average 4,500 MWh per month (1979) to about 6,600 MWh per month (1988). From 1987 to June 1988 this usage varied only 6% from month to month. A PRISM analysis of the campus electricity use could not detect any significant weather-dependence. Hence, a moving average analysis of the Campus electricity use is displayed in Figure 10. In Figure 10 a 46% increase in electricity use occurred from 1978 to 1989 with 30% of that

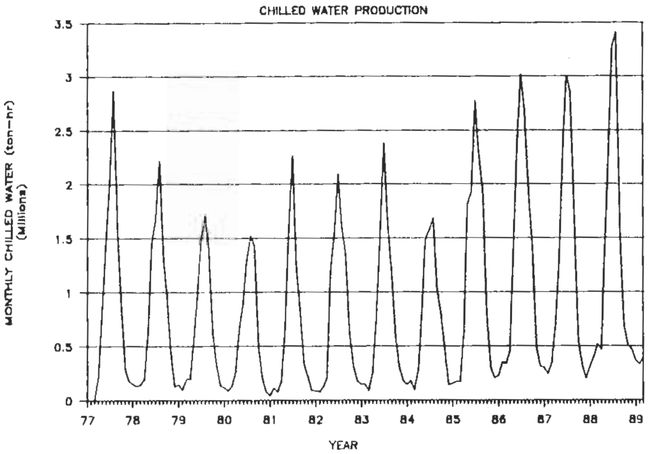

FIGURE 3 - Monthly total chilled water production for the period April 1977 through March 1989. The values displayed represent the actual total chilled water produced by the campus distribution system.

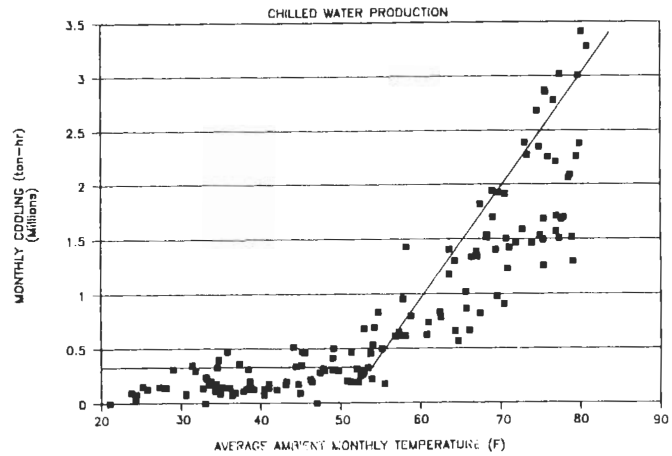

FIGURE 4 Here we show the chilled water production displayed against the average monthly ambient temperature together with the PRISM cooling only (CO) model fit of the data (solid line) for the period July 1987 to June 1988. The slope, base level and balance point temperature are listed in Table 2.

increase occurring from 1985 to 1988.

Electric demand in 1988 for the campus averaged 13 MW per month, varying from a low of 12 MW (March 1988) to a high of 16 MW (September 1988) as shown in Figure 9. In the last two years, electric demand has peaked in either September or October -- most likely due to combined cooling-related and student-related loads.

Annual Weather-normalized Indices. Since records concerning the conditioned square footage of campus were kept in yearly increments, the next step involved annual weather-normalized indices. Figure 11 indicates annual weather-normalized indices (using PRISM) for non-cooling steam production and chilled water production. Electricity consumption is also plotted, but represents the unadjusted usage. In Figure 11 the unadjusted consumption is also shown for steam and chilled water to show the value of weather normalization. Standard errors are shown as dashed lines for non-cooling steam and chilled water. For example, in the case of non-cooling steam production -- without normalizing, one might have inferred a 6.2% reduction from 1982 to 1983. However, the normalized steam production indicated a slight 3.7% increase from 1982 to 1983.

ADJUSTING FOR CONDITIONED AREA.

Next, the annual, weather-normalized consumption was divided by the cumulative conditioned areas it served. Since the campus buildings may receive some combination of steam, chilled water or electricity this involved a separate index for each. The cumulative floor areas for buildings receiving steam, chilled water and electricity for the period 1978 to 1988 are shown in Figure 12. During this 10-year period the total campus conditioned area increased by 10% from 5.6 million ft^2 to 6.2 million ft^2. Area for buildings receiving steam for heating and base-level purposes (i.e., domestic water heating, process loads, etc.) increased by 8% from 5.0 million ft^2 to 5.4 million ft^2. Square footage for buildings receiving chilled water from the central plant increased by 13% from 2.5 million ft^2 to 2.8 million ft^2. Area for buildings receiving electricity from the campus distribution system increased by 12% from 4.8 million ft^2 to 5.4 million ft^2 (Certain buildings on Campus receive electricity directly from the supplier and were not accounted for in this index).

Figure 13 displays the results of dividing the weather-normalized annual energy use by the appropriate conditioned area for total steam, chilled water and electricity consumption. Reducing the previously complex databases (compare with Figures 2, 3, 6, and 9) to this simple representation (i.e., average annual energy intensity in W/ft^2) provided the Campus administrators with the ability to assess comparisons of annual energy use across fuels.

During this 10-year period (i.e., July 1978 to June 1988) normalized non-cooling steam production increased by 11%. A closer look at the sliding PRISM HO parameters (i.e., NAC, heating-related & base-level usage -- not shown) reveals that this is primarily due to non-cooling-related, base-level loads (i.e., steam loads that are not influenced by weather conditions nor consumed by the chilled water plant). Aging steam converters and a need for increased steam-trap replacement are the primary candidates thought to be responsible for the increasing steam consumption.

Normalized chilled water consumption increased by 36% over this 10-year period. Interim trends are also apparent, namely, a 33% weather-related decrease from 1978 to 1981 (i.e., the cooling-portion of the PRISM CO analysis decreased, as shown in Figure 5) followed by a 65% increase in total chilled water consumption from 1984 to 1987, and finally a 7% decrease in consumption from 1987 to 1988 (due to a decrease in cooling load).

The dramatic 1984 to 1987 increase in chilled water consumption corresponds to the commissioning

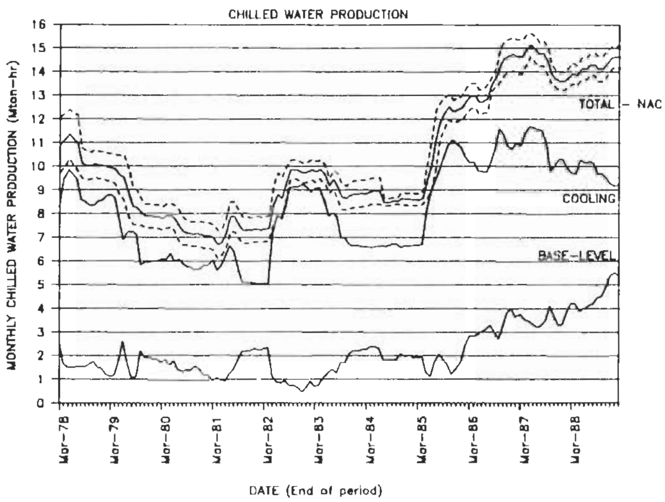

FIGURE 5 Sliding PRISM cooling-only (CO) analysis for the total campus chilled water production for the period June 1978 through July 1988. Values shown represent the Normalized Annual Consumption (NAC), the cooling portion of the annual consumption and the base-level portion of the annual consumption. The dashed lines represent standard errors for the total consumption.

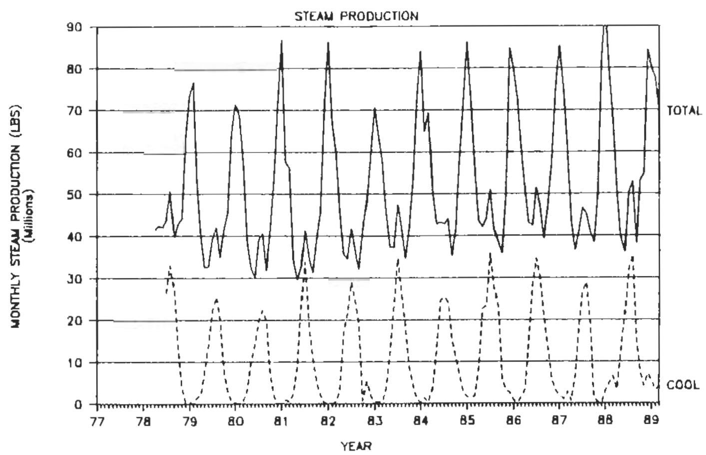

FIGURE 6 This figure shows the total unadjusted, steam production (TOTAL) and sub-metered steam used by the steam-driven chillers in the chilled water plant (COOL) for the period April 1978 through March 1989.

of two new laboratories and a new HVAC system in the art museum. The laboratory buildings contain numerous fume-hoods requiring 24-hour-per-day, 100% outside-air and the art museum contains a special climate control system for precious-art objects that requires special temperature and relative humidity control. The increased normalized campus cooling levels would indicate that sub-metered data on these sites might be justified.

Finally, normalized electricity consumption increased by 42% with 22% of the increase occurring during the three year period from 1985 to 1988. A large portion of the increase during 1986 corresponds to the commissioning of a new electric chiller in the central plant. Clearly, analyzing the sub-metered data on the electricity consumed by the chilled water plant would be justified.

WHAT'S NEXT: DAILY MONITORING OF THE BOILER PLANT.

With the goal of improving the daily operation of the Boiler Plant, a computerized daily logbook is currently being developed. The logbook (based on an earlier prototype -- Englander 1987), combines a graphical user interface with a data base management system and provides data entry, error checking, data analysis, report generation, and data browsing capabilities. The system is designed to be easy for a plant operator (with no previous computer experience) to learn and use. Daily values (e.g., integrator readings, oil tank dipstick measurements, steam pressure and temperature, etc.) are entered once-per-week by the Boiler Plant manager. Figure 13 shows a sample data entry page from the logbook meant to be used by the Plant manager. Control of the on-screen functions is accomplished by "clicking" on the appropriate icon (using a mouse). This system will provide immediate feedback, including daily notes and summaries, and will produce graphs and monthly consumption summaries. The system will enable automatic adjustment for changes in operational parameters such as meter constants.

The intention of the logbook is to bridge the gap between present manual procedures and a fully-computerized control and monitoring system. The primary objectives are to provide immediate feedback to the plant operators and improve the efficiency of the plant management by reducing the time spent manually calculating daily fuel consumptions, efficiencies, etc. Careful design of such a system will allow the computer to perform calculations, store daily trend information and quickly display "canned" graphs (Figure 14). Data are stored in electronic format, which means that reports and historical consumption trends can be produced for later analysis -- a process that previously required hours of manual calculations and was only performed on a monthly basis.

Such a system can also provide for a comparative analysis of energy consumption (Haberl et al. 1989, Haberl and Vajda 1988) which would further enhance the ability of the plant operators to track and diagnose problems. The computerized logbook is valuable because it allows for problems to be detected quicker and allows plant management to focus their attention on daily operation instead of spending time performing these calculations by hand.

DISCUSSION

Constructing these indices is simple. When applied to the consumption for an entire campus, however, it require merging data from many sources, including 15-minute electric demand data, daily boiler records, monthly utility records, historical campus growth, and local weather records.

The experience gained during this process has

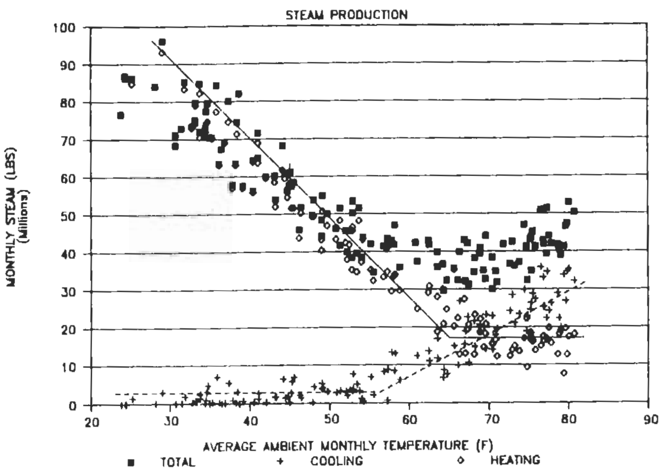

FIGURE 7 Total steam production (TOTAL), steam consumed by the chilled water plant (COOLING) and non-cooling steam inferred by subtracting sub-metered steam from the total steam (HEATING) displayed against the average ambient monthly temperature. The PRISM heating only (HO) model (solid line) and PRISM cooling only (CO) model (dashed line) for the period July 1987 to June 1988 are also indicated. The PRISM CO and HO parameters are listed in Table 2.

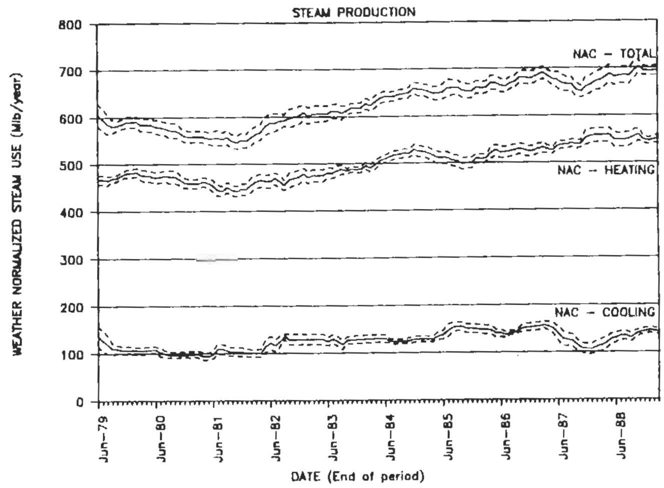

FIGURE 8 - This figure shows the combined total, heating and cooling normalized annual steam consumption (NAC). The dashed lines are standard errors. The total NAC represents the addition of the heating and cooling NACs.

also been rewarding. Prior to the assembly of the indices, concise statements about increasing (or decreasing) campus energy consumption were difficult to make and almost impossible to convey to diverse groups (i.e., engineering, plant operations, campus financial executives, etc.). The indices have simplified this task and help to provide easily understood graphic trends. (One can easily obtain a sense of this by realizing that the three indices in Figure 13 represent data that previously required being displayed as several plots, Figures 2, 3, 6, and 9.) Finally, in a large facility like the Princeton Campus, such indices can help to focus limited resources on those problems where they are most needed. In this case, several of the probable causes for increasing consumption had been previously known. The indices used in this analysis conveyed new information that helped campus facilities management quantify the benefits of addressing these problems.

We have attempted to show that normalizing for varying weather conditions using PRISM, along with adjusting for conditioned floor area, yields 10-year annual indices that help to convey whether or not energy consumption for a campus is increasing or decreasing regardless of varying weather conditions or new construction activities. The whole-campus energy consumption, thus characterized, uses ten parameters: slope, base-level and balance-point temperatures for steam and chilled water consumption in addition to average electricity use.

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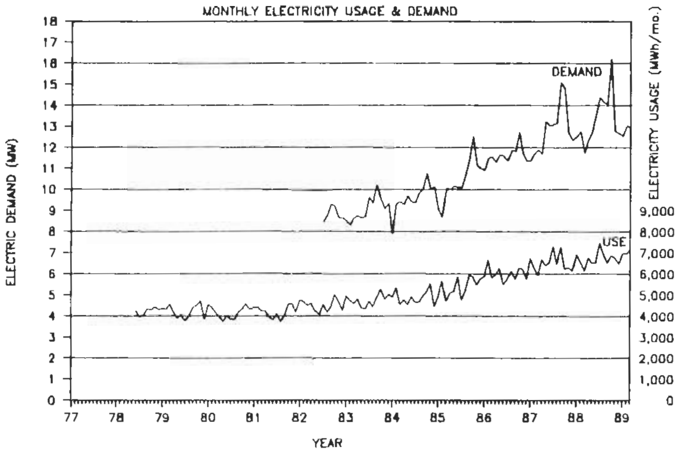

FIGURE 9 - Total actual (non-weather adjusted) campus electricity use (MWh) and electric demand (MW) for the period June 1978 through March 1989.

assistance from Dylan Thurston. We would also like to thank our fellow researchers at CEES for helpful comments. Jeff Haberl (during the course of this work) Scott Englander and Cathy Reynolds are researchers at CEES, Mike McKay and Tom Nyquist are with the Campus Facilities Engineering. Mr. Haberl is now at Texas A&M's Energy Systems Group.

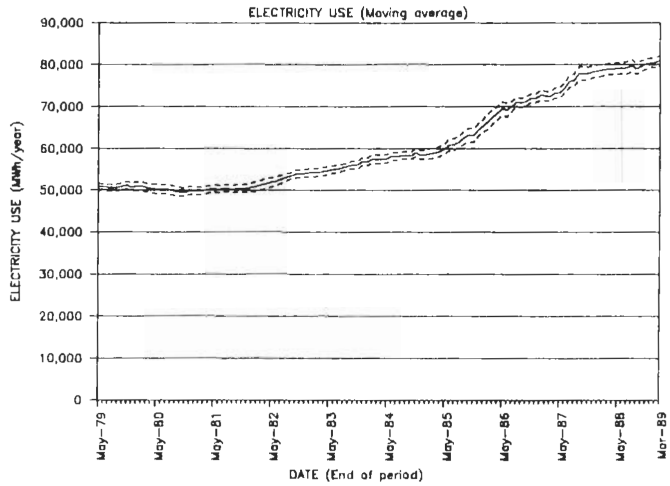

FIGURE 10 - This figure displays a moving average of the campus electricity usage for the period June 1979 through March 1989. The moving average represents a 12-month average applied in successive 12-month increments. The dashed lines are standard errors.

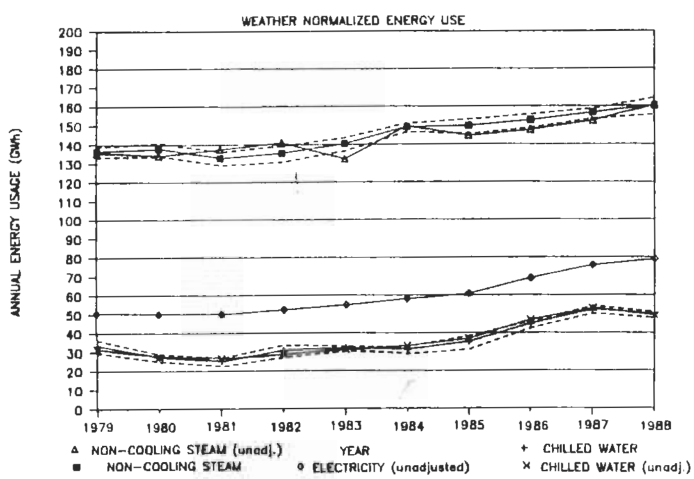

FIGURE 11 - Annual, weather-normalized non-cooling steam and chilled water use for the period 1979 to 1988 (July to June intervals). Average electricity use is also shown for comparison. The triangular and "x" symbols represent the unadjusted consumption for the steam and chilled water, respectively.

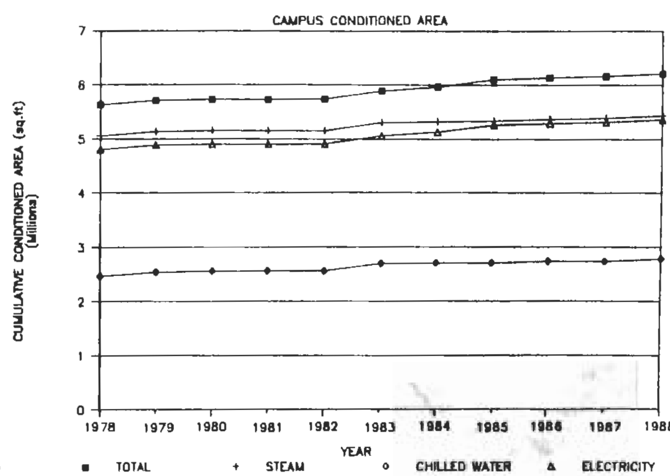

FIGURE 12 - This figure shows the growth in conditioned area for the period 1978 to 1988. Values are shown for the total campus square footage (TOTAL), square footage for those buildings heated with steam from the central plant (STEAM), square footage for those buildings cooled with chilled water from the central plant (CHILLED WATER) and square footage for those buildings receiving electricity from the Campus distribution system (ELECTRICITY).

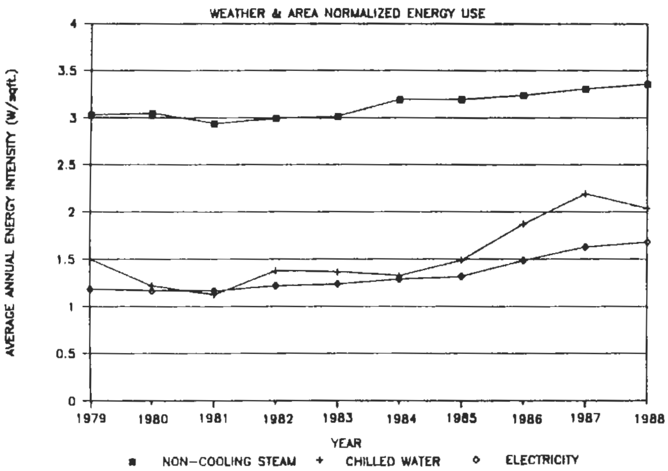

FIGURE 13 - Princeton University campus energy consumption normalized for weather and adjusted for differences in conditioned area. Values are shown for non-cooling steam (NON-COOLING STEAM), centralized chilled water (CHILLED WATER) and electricity from the campus distribution system (ELECTRICITY). Energy conversions used were 1,000 Btu/lb (steam) and 12,000 Btu/ton-hr (chilled water), and 3,413 Btu/kWh.

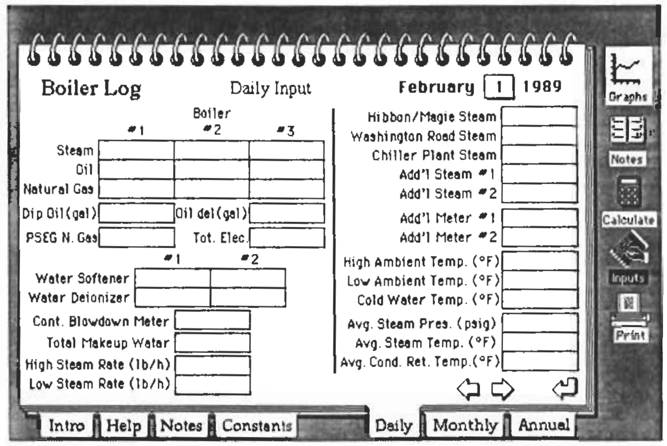

FIGURE 14 - Here we show the prototype computerized logbook which is being developed for the Boiler Plant personnel. Daily data are transferred from log sheets maintained by the staff. Graphs, calculations, corresponding notes and printouts of consumption are a few of the possible outputs of the data from this logbook.

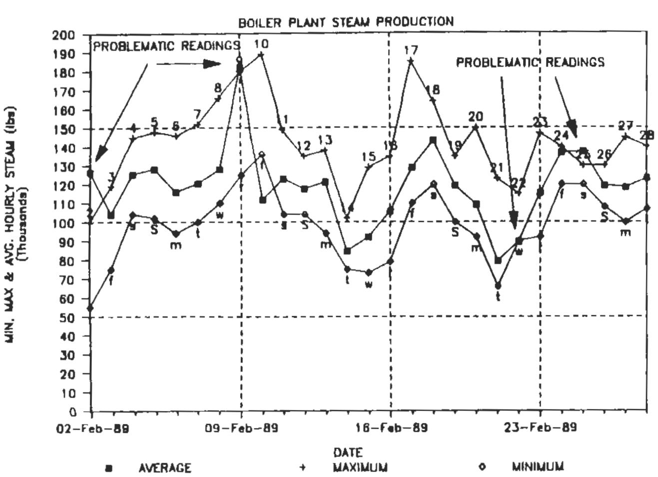

FIGURE 15 - This graph is typical of the types of graphs possible with the Boiler Plant computerized log book. Here we show minimum, maximum and average boiler production rates for the period February 2, 1989 through February 28, 1989. This graph also shows one of the error-checking capabilities -- testing the accuracy of the input data by comparing minimum, maximum and average hourly steam rates.