Total Utility Savings from the 37,000 Fixture Lighting Retrofit to the U.S. DOE Forrestal Building

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In September of 1993 a 36,832 fixture lighting retrofit was completed at the United States Department of Energy Forrestal complex in Washington, D.C. This retrofit represents DOE's largest project to date that utilizes a Shared Energy Savings (SES) agreement as authorized under Public Law 99-272[1] As DOE's first major SES contract, it was important that every aspect of this project serve as the cornerstone of DOE's Federal Relighting Initiative, including the careful measurement of the electricity and thermal energy savings.

Since this project represents one of DOE's first major SES projects, special effort was given to carefully measuring every aspect of the project in order to create a well documented case study to serve as a model for all federal agencies. One of these efforts, initiated in 1991, included measuring hourly electricity and thermal savings using pre-post, whole-building measurement techniques developed as part of the Texas LoanSTAR program[2].In September of 1991, whole-building hourly monitoring equipment was installed and used to develop an hourly baseline record of pre-retrofit, whole-building energy use. Monitoring continued through August of 1995, twenty four months after the September 1993 retrofit completion date.

This paper provides an overview of the lighting retrofit and the resultant electricity and thermal savings. It presents results from the whole-building monitoring effort that show the measured gross electricity savings from the lighting retrofit performed within 90% of the pre-retrofit estimated savings, and that measured reductions in monthly peak hourly electric demand performed within 80% $\pm$ 10% of pre-retrofit estimated demand reductions. Quite surprisingly, the thermal savings which were not included in initial estimates by the USDOE accounted for approximately 24% of the overall savings and increased the total cost savings to $427,529 (107% of the pre-retrofit electricity cost savings estimate).

INTRODUCTION

The James Forrestal building, located at 1000 Independence Avenue, Washington, D.C., comprises interconnected north, south and west wings, and a newly built Child Development Center[3] directly south of the cafeteria. The north wing of the Forrestal complex is elevated three stories above Independence Avenue and is composed mostly of executive offices. The south building surrounds an interior courtyard and contains office space, several small cafeterias, and an employee gym. The west building is composed mostly of a cafeteria and related services. Additional information can be found in Haberl et al. (1995) and Haberl and Bou-Saada (1996).

The 1,632,000 ft^2 (151,617 m^2) facility contains 315,000 ft^2 (29,264 m^2) of parking and 1,317,000 ft^2 (122,353 m^2) of office space and corridors. The Forrestal building receives steam and chilled water from the Central Heating and Refrigeration Plant operated by the General Services Administration (GSA) located a few blocks to the southwest of the Forrestal building. Steam is metered at the Forrestal building with an electronic, insertion-type, axial, turbine steam meter. The chilled water is metered both at GSA's central plant and at the Forrestal building using permanently-mounted, clamp-on ultrasonic meters. Electricity and natural gas are metered separately within the building and are provided by local suppliers. Potable water is also metered on-site[4].

Perimeter heating and cooling is provided by two primary types of systems: four-pipe fan coil units (south and west exposure), and two-pipe fan coil units. Other specialty systems include reheat coils, baseboard units (cafeterias and corridors), north building (fourth floor) hydronic slab heating[5], heating and ventilating unit heaters (garage), and specialty computer room cooling systems. Ventilation and cooling for the building is provided by a low-pressure, constant volume air distribution system serviced by air-handling units located in 22 mechanical rooms throughout the building. Hot water is supplied by four steam-fed domestic water converters. Three of the converters supply 105 °F (40.6 °C) water for lavatories and one supplies 140 °F (60.0 °C) water for kitchen use.

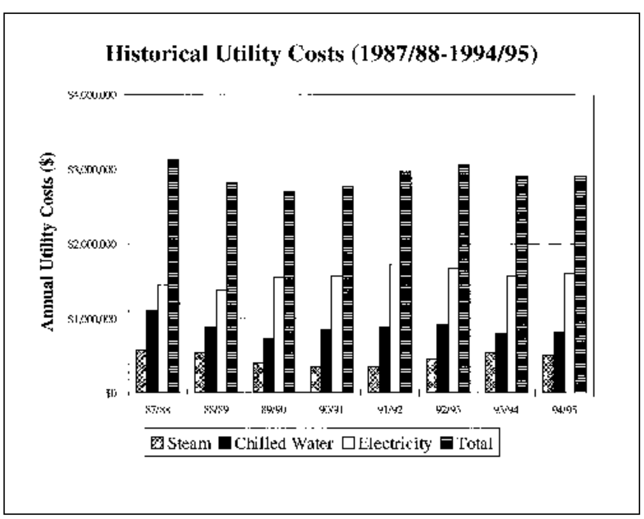
Prior to 1992, control of systems at the Forrestal building was provided by effective manual schedules, timeclocks, and local pneumatic controllers. In 1993 a state-of-the-art computerized Energy Management and Controls System was installed and now performs the basic functions that the previous manual system performed[6]. Normal business hours for the 4,400 employees are from 6:30 a.m. to 6:30 p.m., Monday through Friday[7].

Energy Conservation Efforts at the Forrestal Building (1986–1995)

In FY 1992/93 the total utility costs for the Forrestal building were $3,054,957, or $2.31 per square foot ($24.97 per square meter)[8]. Figure 1 provides a summary of the utility costs from FY 1987/88 through FY 1994/95. Figures 2a and 2b show the monthly electricity use and peak electric demand, respectively. Figures 2c and 2d show the monthly steam use and chilled water from utility billing records, respectively[9]. These figures are shown versus average monthly dry bulb temperature for comparison. Prior to the lighting retrofit the average monthly electricity use for the Forrestal building increased by roughly 400 MWh/mo over an eight year period from 1985 through 1993. It is believed that this is due to the large numbers of personal computers, printers, and office equipment that were purchased and installed during this period. A similar increase can be seen in the peak monthly electric demand for the building which reached a peak of 5,777.3 kW in July of 1992.

In Figure 2c dramatic reductions in steam energy use can be seen beginning in 1986 when the Forrestal's maintenance staff began an aggressive steam trap and steam converter maintenance program and initiated the shutoff of steam during the weekends when heating was not required[10]. This reduction in steam use resulted in an annual savings of over $250,000 per year. Due to the diligence of the Forrestal staff, the reduction has persisted for nine years since it was first initiated during the winter of 1986/87, which amounts to a total cumulative savings in excess of $2,250,000.

Figure 1. *Historical Utility Costs 1987–1995. This Bar Graph Shows the Historical Utility Costs from FY 1987/88 Through FY 1994/95. The Forrestal Complex Consumes Steam, Chilled Water, Electricity, and Potable Water (Not Shown)*



Steam energy use continued to decline until the 1994 heating season when it increased by about 21% over the previous year to make up for the decreased heat coming from the newly installed lights. The monthly chilled water consumption for the Forrestal building also increased during this period due mostly to weather conditions. The increased cooling load from the constant addition of personal computers may also have added to the Forrestal building's cooling load[11]. A weather normalized analysis of the thermal savings is shown later in this paper.

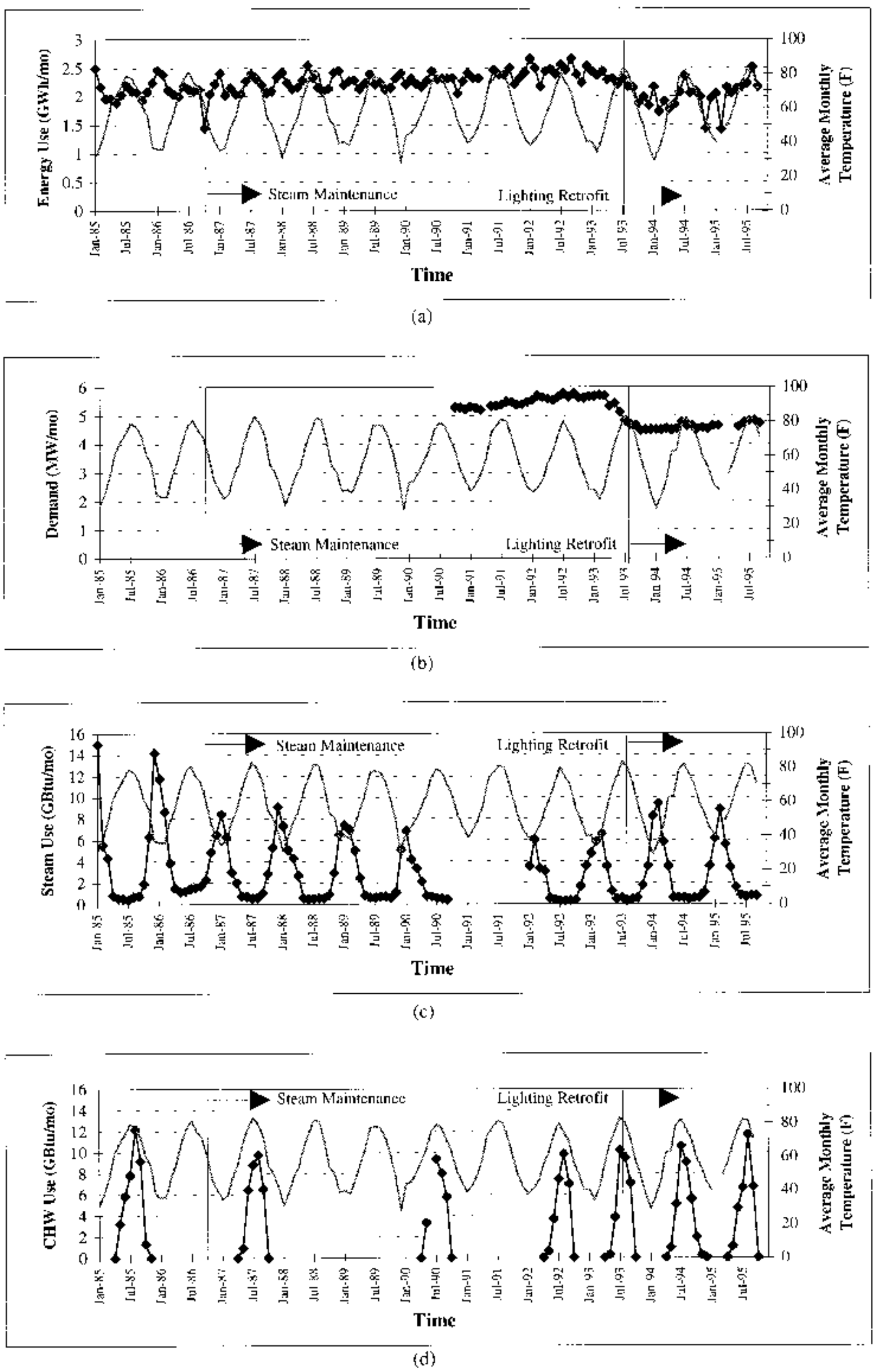
Overview of the 37,000 Fixture Lighting Retrofit

In 1989 a Shared Energy Savings lighting retrofit project was proposed for the Forrestal building that would reduce energy costs at DOE's headquarters building and serve as a demonstration project for the planned Federal Relighting Initiative. As part of the demonstration effort DOE initiated several parallel efforts to document the electricity and thermal savings from the lighting retrofit, including portable before-after, end-use measurements of the lighting loads, a lighting test demonstration room, and long-term whole-building energy measurements. In 1990 DOE established end-use electricity estimates for the Forrestal building using portable RMS electrical data loggers and whole-building data from the local utility's 15-minute electricity demand data (Mazzucchi 1992)[12].

Qualified bidders were then asked to demonstrate their proposed lighting fixtures in a specially equipped room where the same RMS electrical data loggers had been installed to monitor the electricity use and power quality of the lighting fixtures. Lighting quality measurements were also taken to evaluate the different proposals (Halverson et al. 1993a, 1993b, 1994). Finally, in order to supplement the before-after, snap-shot, end-use measurements, baseline whole-building electricity, and thermal measurements were initiated in September of 1991 using hourly monitoring equipment[13].

A lighting retrofit contractor was then chosen in November 1992 and the installation of new lighting fixtures began on March 12, 1993. The majority of the lighting fixtures were installed by July 31, 1993. Final completion of the project occurred on September 30, 1993. Post-retrofit, RMS electrical measurements were then reapplied to the same lighting panels throughout the Forrestal building to establish 24-hour,

Figure 2a–d. *Monthly Utility Billing Data for the DOE Forrestal Complex. The First Two Graphs (Figure 2a and 2b) Show the Monthly Electricity Use and Peak Electric Demand for the Forrestal Building from January 1985 Through September of 1995. Figure 2c Shows the Monthly Steam Consumption and Figure 2d Shows the Chilled Water Use from January 1985 Through September of 1995. Average Monthly Temperature is also Shown as a Solid Line*



weekday-weekend post-retrofit lighting profiles[14]. Whole-building electricity and thermal energy use measurements continued through August 1995 and are the basis for the current paper.

The Department of Energy estimated that the lighting retrofit would reduce annual electricity use by 6.146 million kWh (62% of the lighting electricity use), and lower peak electric demand by 1,300 kW. Initial estimates of the electricity cost savings were $399,058 per year, or $1,350,386 over a seven year period[15]. Environmental impacts of this project have been estimated in the range of 3,791 to 4,160 tons/yr (3.4 to 3.8 million kg) of carbon dioxide (CO_2) avoidance, 31.7 to 33.2 tons/yr (28.7 to 30.1 thousand kg) of sulfur dioxide (SO_2) avoidance, and 13.6 to 16.0 tons/yr (12.3 to 7.3 thousand kg) of nitrous oxide (NO_2) avoidance[16].

Significance of Measuring the Savings. Unfortunately, to the dismay of many building owners and energy service companies, cost savings from unadjusted utility bill comparisons do not always match the negotiated dollar savings from a shared energy savings contract. Although the trade journals are usually quick to print the estimated SES success stories, rarely do they follow up to report the measured savings. Without the extra assurance that careful measurement provides, many contracts end up in costly litigation. This probably would have been the end result for the Forrestal building had the DOE not had the foresight to accurately measure the savings. Clearly, had the Forrestal staff been looking only at the monthly cost difference between the two years, they would have had cause for alarm because none of the months showed savings that equaled or exceeded the average projected savings ($399,000/yr or $33,000/mo).

METHODOLOGY

The methodology that has been applied to calculate the gross, whole-building electricity, and thermal savings from the lighting retrofit uses a before-after analysis of the whole-building electricity and thermal use. This methodology separately calculates weather-dependent and weather independent energy use by developing empirical baseline models that are consistent with the known loads on a given channel.

In the weather independent procedure, a baseline statistical model of the 1992 weather independent energy use was calculated using 24-hour, weekday-weekend hourly profiles and is shown with more detail in Haberl et al. (1995). The hourly electricity savings were then calculated by forecasting the pre-retrofit baseline electricity use into the post-retrofit period and summing the hourly differences between the pre-retrofit and post-retrofit models using a modification to the procedure outlined in Claridge et al. (1992). In general, several passes are required through the data set to determine the best number of 24-hour profiles that accurately represent the building's electricity use using an iterative procedure[17] that attempts to select the fewest number of 24-hour profiles to adequately characterize the building's 24-hour profiles. A model is deemed adequate when the model-predicted electricity use matches the actual electricity use to an appropriate goodness-of-fit as determined by the coefficient of variation of the root mean square error CV(RMSE) and mean bias error (MBE)[18].

The weather-dependent procedure calculated a baseline statistical model of the 1992/1993 pre-retrofit energy use with four parameter heating and cooling change point models based on monthly utility data and average monthly temperatures. The thermal savings were then statistically calculated by forecasting the baseline thermal use into the post-retrofit temperature period and calculating the difference between the pre-retrofit model and post-retrofit measured data (Kissock et al. 1994).

Applying the Data Collection Procedures to the Forrestal Building

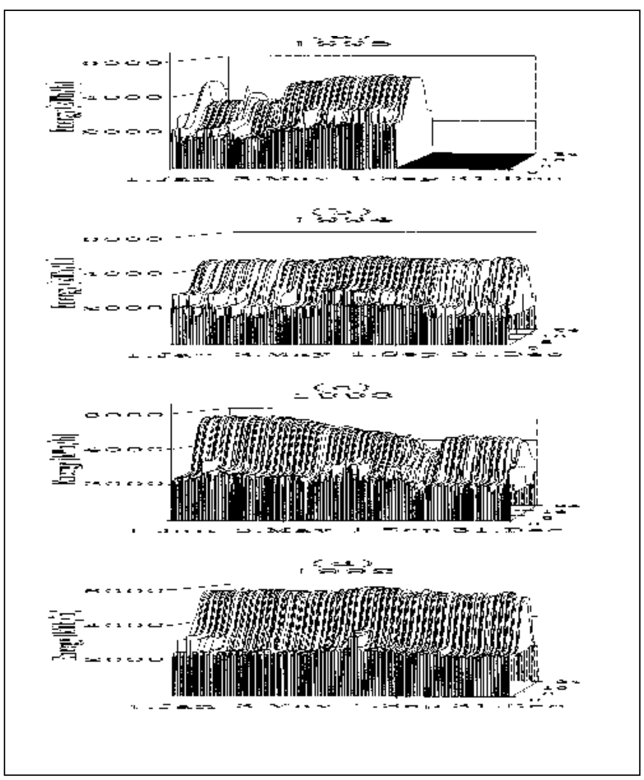
In the Fall of 1991 long-term monitoring equipment was installed in the Forrestal building to measure the hourly whole-building electricity, chilled water, and steam energy use. Hourly weather data were also recorded during this period from the National Weather Service (NWS) using data from the nearby National Airport weather station[19]. Whole-building electricity use was recorded with a single KYZ pulse using a shared signal from the utility's pulse accumulator that collects the pulses from the four 13.2 kV electricity feeders into the building[20]. Submetered electricity was also measured for selected motor control centers (MCC), elevator panels, lights and receptacles, and for the USDOE Child Development Center (CDC). Additional monitoring was also conducted on the CDC using a separate logger installed in 1991 to determine the effectiveness of the energy conservation measures that had been designed (Bou-Saada 1994; Haberl and Bou-Saada 1993).

Thermal metering consisted of chilled water and steam flow measurements. Chilled water was measured with a permanently installed Btu meter which integrated whole-building flow measurements from an ultrasonic meter with supply and return temperatures. Steam measurements were taken by an insertion-type axial turbine steam meter located in the building's 250 psi (1,724 kPa) steam supply. Meter calibrations were performed by comparing chilled water and electricity measurements against measurements taken by GSA and the local electric utility[21]. Steam meter calibrations were performed periodically by the GSA. Data from three loggers were collected weekly, plotted and inspected visually for errors using automatic routines developed as part of the Texas LoanSTAR program (Lopez and Haberl 1992).

Electricity Data Collection. Figure 3 shows the hourly whole-building electricity data collected from the site for the period January 1992 through August 1995 as juxtaposed 3-D time series plots. In these plots the day of the year is located left to right along the x-axis and the time of day is located along the y-axis (i.e., time runs into the page). The energy use is the height of the surface above the x-y plane.

Clearly, several features can be seen in the data. First, prior to the retrofit in 1993 the whole-building electricity profiles were very uniform with the exception of only a few days during the year when air-handling units were run longer than normal. These periods occurred during severe winter and summer conditions when it was necessary to run the main air-handlers longer to help maintain comfort conditions in the building. Prior to the retrofit, this was necessary during extreme summer conditions because the building's cooling system was running at its rated capacity which required that the air-handling systems operate 24 hours-per-day to maintain conditions. During extreme winter conditions the air-handling units were run continuously to avoid freeze damage of the cooling coils in the air-handling units.

Figure 3a–d. *Whole-Building Electricity Use for the DOE Forrestal Complex. These Graphs Show the Measured, Whole-Building Electricity Use for the Forrestal Complex from January 1992 Through August 1995 Displayed as an Hourly 3-D Time Series Plot*



Beginning in March 1993 and continuing through August 1993 the reduction in whole-building electricity use attributed to the retrofit can be clearly seen. However, beginning in September of 1993 the whole-building electricity data became erratic fluctuating randomly by about 1,000 kW and then continuously dropping for no apparent reason. After some investigation it was determined that one of the local utility's mechanical KYZ pulse initiators on the four 13.2 kV feeders had failed.

Unfortunately, shortly after the pulse initiator was fixed it failed again and continued to fail periodically throughout the remainder of the post-retrofit monitoring period. This finally stopped in April, 1995 when the meter was replaced with a new electronic meter. This problem was further compounded by maintenance power outages[22] that were initiated in 1993 and continued through 1994. Both of these problems contributed to abnormal usage profiles that necessitated the use of empirical pre-retrofit and post-retrofit models to measure the lighting retrofit savings.

Thermal Energy Data Collection. In addition to measuring hourly electricity consumption at the Forrestal building, hourly steam and chilled water data were measured and recorded. A significant amount of steam data were recorded for the pre- and post-retrofit periods to complete a successful analysis. A complete set of post-retrofit chilled water data were not available due to a malfunctioning chilled water meter leaving only a partial dataset for analysis. As a result, monthly utility bills were used for the analysis of the steam and chilled water energy use. Ideally, hourly measured data would provide more accurate results.

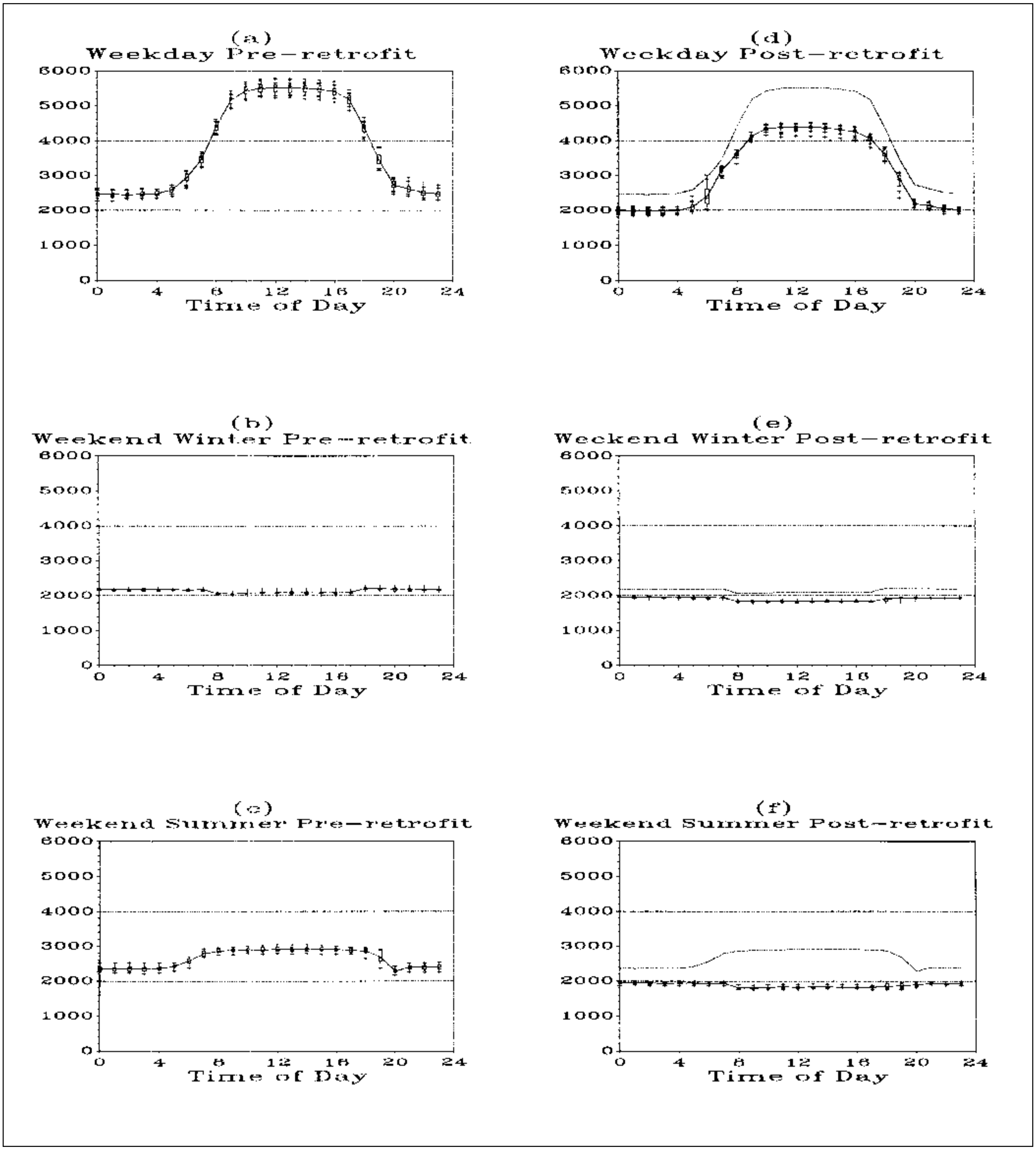
ELECTRICITY SAVINGS RESULTS

One of the most prominent features of the 1992 electricity baseline data shown in Figure 3 is the lack of any significant weather dependency. To some extent this was to be expected since the building receives its chilled water from the GSA central plant and therefore does not contain any significant cooling related loads that normally would have been associated with the electricity required to run a large chiller plant[23]. This lack of any weather dependency meant that the whole-building electricity use could be accurately modeled with weather independent 24-hour daytype profiles.

Development of the 24-Hour, Pre-Post, Weekday-Weekend Electricity Profiles

Using the methodology developed by Thamilseran and Haberl (1995) it was determined that three 24-hour daytype profiles would be required to characterize the electricity use for the 1992 baseline period as shown in Figure 4, a weekday profile (i.e., the upper plot), a winter weekend profile (middle

Figure 4a–f. *Whole-Building Pre-Post, Weekday-Weekend 24-Hour Daytype Box-Whisker-Mean Profiles for the DOE Forrestal Complex. These Figures Show the 24-Hour Statistical Daytype Profiles of the Whole-Building Electricity Use for Three Daytypes (Weekday, Weekend-Winter, Weekend-Summer) During Pre-Retrofit and Post-Retrofit Periods. The Dashed Lines on the Post-Retrofit Plots are the Transposed Means of the Pre-Retrofit Period Used for Comparison*



plot from October 1 through May 31 of the following year), and a summer weekend profile (lower plot from June 1 through September 30). The extremely tight inter-quartile range for each of the 24 bins and CV(RMSE) of 6.22% indicated that this was an adequate choice of day-type profiles for the pre-retrofit period as well as the post-retrofit period[24]. Furthermore, an RMSE of 208.75 kWh/h[25] indicated that the model was capable of measuring the pre-retrofit estimated 1,300 kW demand savings. The presence of the previously mentioned problems in the whole-building post-retrofit period is evident in this plot as well as the drop in the CV(RMSE) to 14.67%.

The major period of bad data from the faulty utility meter occurred in September of 1993 and can be seen in the third plot of Figure 3. To compensate for the bad data in the 1993/94 post-retrofit period a post-retrofit model was developed from representative data for the period immediately after the retrofit of October 1, 1993 to November 30, 1993[26]. This post-retrofit model consisted of one weekday profile and winter-summer weekend profiles. These can be seen in the right hand plots in Figure 4. The CV(RMSE) of 5.66% indicates that the post-retrofit model adequately described the post-retrofit data occurring during the October–November 1993 period. The savings from the lighting retrofit were then calculated by comparing annual electricity use predicted by the 1992 pre-retrofit model against the annual electricity use predicted by the post-retrofit model.

Savings were tabulated and compared against the savings calculated by subtracting adjusted utility bills[27]. The savings calculated by simply comparing the utility bills for the 12 month period was 5.532 million kWh. The total savings calculated using the pre-post daytypes for the 12 month period from August 1993 to July 1994 is 5.520 million kWh which is about 10.2% below the pre-retrofit estimated savings of 6.146 million kWh. The billed demand savings for 1993/94 compared to similar months in 1992 varied from a low of 959.0 kW to a high of 1,186.6 kW. This compares favorably to the pre-retrofit estimated 1,300 kW demand reduction estimate. The modeled demand savings is 1,053 kW/mo and compares well with the billed demand savings. The comparison of pre-post model's hourly CV(RMSE) of 6% to 8% against the annual electricity reduction of 20% indicates that the level of savings is above the statistical noise of the analysis method.

Table 1 is a summary of the modeled monthly and total electricity savings resulting from the lighting retrofit and are based on the number of days included in each month's billing period during the post-retrofit period. Therefore, the months do not show uniform monetary or energy consumption amounts as would be expected when modeled data are coupled with the variable number of weekend days and holidays per month. Each month's energy and demand savings that were calculated using the weather independent bin analysis, are listed along with the monetary savings based on the utility rates that were charged during the pre-retrofit period. The PEPCO rates shown in Table 2 are calculated using a rate schedule composed of three distinct energy charges and two demand charges[28].

According to Table 1, it may be observed that the summer months of June through October produced the highest energy savings while the utility summer rate schedule was in effect. Since a more efficient, lower wattage lighting system produced less internal heat gain throughout the building, the overall load on the cooling system was in turn reduced. Furthermore, since the higher savings occurred while the summer rate schedule was in effect, the savings due to the reduced demand are even more significant. Added savings are realized not only in the billed distribution charge but also in the production charge which is billed during the summer rate schedule months. The impact of the avoided cost of demand is easily seen in the demand savings column of Table 1, particularly when the utility company raises rates in coming years. Another significant aspect of lighting retrofits that should not be ignored is the incurred thermal savings illustrated in the next section.

THERMAL SAVINGS RESULTS

Whenever large-scale lighting retrofits such as the Forrestal building take place, it is important to consider the thermal impacts. Lighting systems, especially aging lamps in large quantities, generate a considerable amount of heat when in use. During the winter, the building heat load is reduced because of the heat from the lights; in the summer months, extra space cooling is required to overcome the internal heat as well as the internal heat load generated by the equipment and occupants. To calculate the savings incurred, a weather dependent model was used to normalize for weather.

Four Parameter Weather Dependent Model

Four parameter change-point chilled water and steam regression models were calculated using monthly utility bills and average monthly temperature data. First, the monthly GSA utility bill pre-retrofit data were divided by the number of billing days for each month according to the GSA billing period. A statistical energy calculation software tool, EModel (Kissock et al. 1994), was then utilized to calculate change-point monthly models for cooling and heating periods. The pre-retrofit parameters were then projected into the post-retrofit period using post-retrofit monthly average outdoor dry bulb temperatures. The pre-retrofit model was then subtracted from the post-retrofit GSA utility bills for each month to calculate energy savings.

Table 1. *Summary of Electricity and Demand Savings. The Dollar Savings are Based on the Actual Utility Rates that Were Charged During the Pre-Retrofit Period of January to December, 1992*

Month	Modeled kWh Savings	Modeled kW Savings	Energy Savings	Demand Savings	Total Savings
Aug	540,223	1,053	$18,202	$17,794	$35,996
Sep	522,009	1,053	$20,326	$17,794	$38,120
Oct	421,826	1,053	$16,598	$17,794	$34,392
Nov	427,802	1,053	$14,228	$6,844	$21,072
Dec	404,413	1,053	$16,411	$6,844	$23,255
Jan	429,778	1,053	$13,957	$6,370	$20,327
Feb	472,599	1,053	$13,945	$6,370	$20,315
Mar	442,892	1,053	$14,678	$6,370	$21,048
Apr	421,464	1,053	$13,661	$6,370	$20,031
May	408,789	1,053	$14,872	$6,370	$21,242
Jun	486,381	1,053	$16,783	$16,583	$33,366
Jul	541,384	1,053	$18,379	$17,163	$35,542
TOTAL	5,519,560	12,635	$192,040	$132,666	$324,706

Table 3 and Figure 5 show the four parameter change-point heating model and Table 4 and Figure 6 show the four parameter change-point cooling model that were utilized in this study. By analyzing these graphs, it may be observed that the four parameter models fit the monthly data closely. An extensive comparison between three and four parameter models is included in Haberl and Bou-Saada (1996). The four parameter models of the pre-retrofit chilled water and steam use were then used with the pre-retrofit GSA utility rates to calculate monetary savings.

Table 5 summarizes the thermal savings for the chilled water and the steam use. Tables 6a and 6b include the GSA pre-retrofit and post-retrofit chilled water and steam utility billing data, respectively to demonstrate the monetary savings. The column labeled ''unadjusted GSA CHW savings'' in Table 6a lists the simple difference from one year to the next. This is the savings that would have been realized if one only analyzed the monetary value of the utility bills without taking weather normalization or rate changes into account. The final column labeled ''weather normalized CHW savings'' in Table 6a was calculated by projecting the pre-retrofit CHW use into the post-retrofit period and uses the pre-retrofit CHW costs. Table 7 contains the utility rates charged by GSA for chilled water and steam during the pre- and post-retrofit period. The pre-retrofit rates provided the basis for calculating costs for both the pre-retrofit and post-retrofit periods and thus, the cost savings.

The weather normalized savings in Table 6a for the chilled water are $218,121. The unadjusted total savings of $24,314 lag far below, and even contain negative savings for some months. This is due to a marked increase in the average monthly temperature of the post-retrofit year from the pre-retrofit year coupled with a significant utility rate change.

Table 6b shows the savings or rather the increase in the steam use necessary to make up for the reduced heat from the lights. The major cause for the difference between the unadjusted steam increase of $101,464 and the weather normalized steam increase of $115,297 lies in the utility rate change. Unlike the rising electricity rates contributing to

Table 2. *Utility Rates Charged During the Pre-Retrofit Period on Which the Savings Calculations are Based. The Three Energy Periods Include an Off-Peak Period, an Intermediate Period, and an On-Peak Period. The Two Demand Rates Include a Distribution Rate Charged During the Entire Year and a Production Rate Charged Only During the Summer Rate Schedule from June Through October*

Month	$/kWh Off-pk (1)	$/kWh Interm (2)	$/kWh On-pk (3)	$/kW Distribution	$/kW Production
Jan-92	$0.028329	$0.037259	$0.043204	$6.05	$0.00
Feb-92	$0.028330	$0.037260	$0.043204	$6.05	$0.00
Mar-92	$0.028330	$0.037260	$0.043207	$6.05	$0.00
Apr-92	$0.028329	$0.037260	$0.043203	$6.05	$0.00
May-92	$0.028329	$0.037259	$0.043205	$6.05	$0.00
Jun-92	$0.026380	$0.038020	$0.052214	$6.05	$9.70
Jul-92	$0.027361	$0.039433	$0.054151	$6.30	$10.00
Aug-92	$0.028220	$0.040669	$0.055846	$6.50	$10.40
Sep-92	$0.028220	$0.040670	$0.055846	$6.50	$10.40
Oct-92	$0.028220	$0.040669	$0.055847	$6.50	$10.40
Nov-92	$0.030320	$0.039900	$0.046218	$6.50	$0.00
Dec-92	$0.030319	$0.039899	$0.046215	$6.50	$0.00

(1) Off-peak - WD: 12 a.m.–8 a.m. WE: 24 hours.
(2) Intermediate - WD: 8 a.m.–12 p.m. WD: 8 p.m.–12 a.m.
(3) On-peak - WD: 12 p.m.–8 p.m.

Table 3. *Statistical Goodness-Of-Fit for the Four Parameter Steam Model. This Table Provides the Statistics from the Four Parameter Model Which Were Fit to the Pre-Retrofit Data Using the Emodel Software (Kissock et al. 1994)*

Model Type	No. of Points	R squared (%)	CV-RMSE (%)	RMSE	Baseline	Left Slope	Right Slope	Change Point
4P	12	0.99	10.2	7.7804	16.3976	− 10.7267	− 0.3372	53.86

higher savings seen earlier, the steam rate charged by GSA was reduced from $15.50/MMBtu during the pre-retrofit period to $14.95/MMBtu during the post-retrofit period. The chilled water rate decreased by an average of just over $10/MMBtu from the pre-retrofit period to the post-retrofit period. To uphold consistency with the electricity analysis, the monthly pre-retrofit utility rate was used as a baseline each month in this analysis for both the pre- and post-retrofit

Table 4. *Statistical Goodness-Of-Fit for the Four Parameter Chilled Water Model. This Table Provides the Statistics from the Four Parameter Model Which Were Fit to the Pre-Retrofit Data Using the Emodel Software (Kissock et al. 1994)*

No. of Points	R squared (%)	CV-RMSE (%)	RMSE	Baseline	Left Slope	Right Slope	Change Point
12	0.99	18.8	14.6252	12.9473	0.571	22.0339	62.88

Figure 5. *Four Parameter Steam Model. This Graph Shows the Four Parameter Change-Point Model Fitted to the Monthly Steam Data for the Period 4/92 to 3/93*

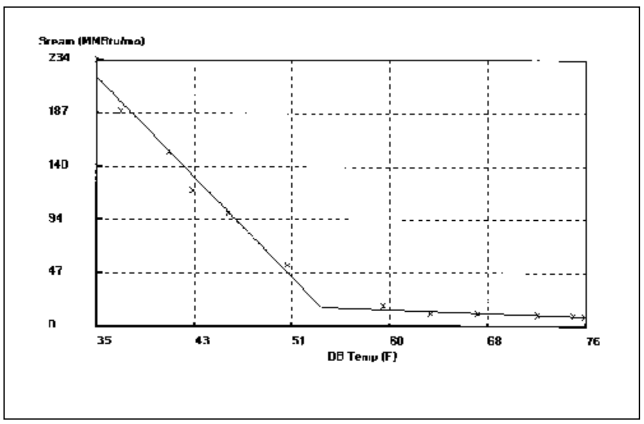
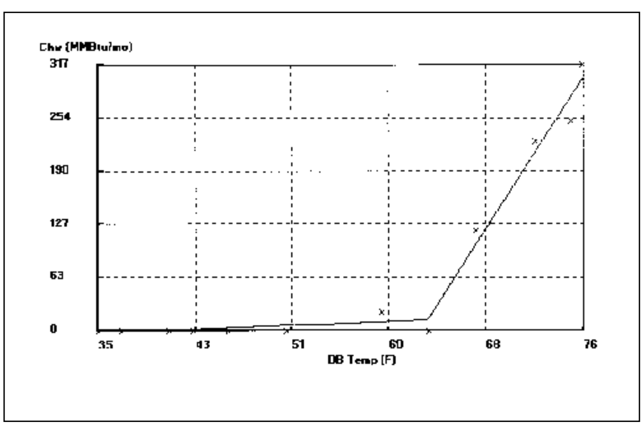


Figure 6. *Four Parameter Chilled Water Model. This Graph Shows the Four Parameter Change-Point Model for the Whole-Building Chilled Water Data During the Period 4/92 to 3/93*



periods savings calculations. This assumption increases the impact of the added steam costs.

Table 8 and Figure 7 compare the individual electricity, chilled water, and steam monetary savings resulting from the lighting retrofit. Figure 7a shows the direct pre/post utility bill comparison without weather normalization or analysis of the electricity data. Figure 7b shows the weather normalized savings calculated with the methods described in this paper. The increase in electricity and chilled water savings are clearly evident. Weather normalized steam costs increased. Table 8 summarizes the monetary savings for the GSA utility bills and the weather normalized analysis.

The importance of analyzing the electricity and thermal savings from the lighting retrofit can be seen in the dramatic increase in the total savings from $201,335 (50% of the pre-retrofit expected cost savings estimate) for the direct utility bill comparison to $427,529 (107% of the pre-retrofit expected cost savings estimate) for the weather normalized savings[29].

SUMMARY AND DISCUSSION

At the present time there is considerable debate concerning how to measure savings from energy conservation retrofits to large buildings. This paper has attempted to shed some light on the effectiveness of using whole-building, or gross measurements[30] of electricity and thermal savings from a lighting retrofit. This paper has focused on the use of pre-post whole-building measurements that could easily be obtained for any building using the existing revenue meters.

Clearly, there are several points that warrant further discussion, including:

(1) Comparisons of unadjusted utility billing costs may not be sufficient to measure savings from lighting retrofits—even when the savings amount to 20% of the annual kWh for a facility. In the case of the Forrestal building, differences in the utility's month to month unit cost factors and billing adjustments obscured the monetary retrofit savings from the decrease in electricity use.

(2) Although portable, snap-shot, before-after end-use measurements can provide an accurate measure of the energy use of an individual device or end-use the uncertainty

Table 5a,b. *Summary of the Chilled Water and Steam Thermal Savings Due to the Retrofit. Table 5a Shows a Monthly Chilled Water Summary of the Unadjusted GSA Monetary Savings and the Weather-Normalized Thermal Savings. Table 5b Shows a Monthly Steam Summary of the Unadjusted GSA Monetary Savings and the Weather-Normalized Thermal Savings*

(a)

Mo	GSA Pre-retrofit Utility Bill (MMBtu/mo)	GSA Post-retrofit Utility Bill (MMBtu/mo)	GSA Change (MMBtu/mo)	4-P Pre-retrofit Model (MMBtu/mo)	4-P Change (1) (MMBtu/mo)
Jan	0	0	0	0	0
Feb	0	0	0	0	0
Mar	0	0	0	0	0
Apr	0	0	0	0	0
May	636	970	334	468	502
Jun	3,685	5,099	1,414	5,948	−849
Jul	7,493	10,576	3,083	12,366	−1,790
Aug	9,830	9,051	−779	10,729	−1,678
Sep	6,998	7,094	96	11,412	−4,318
Oct	0	0	0	0	0
Nov	0	0	0	0	0
Dec	0	0	0	0	0
TOTAL	28,642	32,790	**4,148**	40,923	**−8,133**

(1) This value was calculated by subtracting the Pre-retrofit 4-P model consumption from the GSA Post-retrofit consumption.

(b)

Mo	GSA Pre-retrofit Utility Bill (MMBtu/mo)	GSA Post-retrofit Utility Bill (MMBtu/mo)	GSA Change (MMBtu/mo)	4-P Pre-retrofit Model (MMBtu/mo)	4-P Change (1) (MMBtu/mo)
Jan	4,756	8,216	3,461	7,777	439
Feb	5,848	9,411	3,563	8,775	636
Mar	6,550	5,797	−753	4,322	1,475
Apr	3,100	3,520	420	1,127	2,394
May	545	585	40	399	186
Jun	361	594	233	329	265
Jul	290	585	295	217	368
Aug	276	483	207	256	227
Sep	310	430	120	246	184
Oct	344	552	208	420	133
Nov	1,671	1,730	59	794	935
Dec	3,589	3,540	−50	3,343	197
TOTAL	27,640	35,444	**7,804**	28,005	**7,438**

(1) This value was calculated by subtracting the Pre-retrofit 4-P model consumption from the GSA Post-retrofit consumption.

Table 6a,b. *Summary of the Thermal Utility Billing Data and Monetary Change Resulting from the Retrofit. Table 6a Shows the Chilled Water Savings and Table 6b Shows the Steam Savings*

(a)

Pre-retrofit Period Month	Pre-retrofit GSA CHW Utility Bill	Pre-retrofit Normalized CHW	Post-retrofit Period Month (1)	Post-retrofit GSA CHW Utility Bill (2)	Unadjusted GSA CHW Change	Post-retrofit Normalized CHW (3)	Weather Normalized CHW Change
Apr-92	—	—	Apr-94	—	—	—	—
May-92	$36,068	$26,559	May-94	$25,152	($10,916)	$55,048	$28,489
Jun-92	$151,883	$245,117	Jun-94	$132,220	($19,663)	$210,134	($34,983)
Jul-92	$210,802	$347,856	Jul-94	$274,241	$63,439	$297,509	($50,347)
Aug-92	$301,507	$329,058	Aug-94	$234,690	($66,817)	$277,591	($51,467)
Sep-92	$177,977	$290,207	Sep-93	$187,620	$9,643	$180,395	($109,812)
Oct-92	—	—	Oct-93	—	—	—	—
Nov-92	—	—	Nov-93	—	—	—	—
Dec-92	—	—	Dec-93	—	—	—	—
Jan-93	—	—	Jan-94	—	—	—	—
Feb-93	—	—	Feb-94	—	—	—	—
Mar-93	—	—	Mar-94	—	—	—	—
TOTAL	$878,237	$1,238,797		$853,923	($24,314)	$1,020,676	($218,121)

(1) The sequence of the months wraps around to facilitate direct monthly comparisons from the pre-retrofit period to the post-retrofit period.
(2) The dollar values are calculated based on actual utility billing data and rates from the pre-retrofit period to the post-retrofit period.
(3) The post-retrofit normalized costs are based on pre-retrofit utility rates.

(b)

Pre-retrofit Period Month	Pre-retrofit GSA Steam Utility Bill	Pre-retrofit Normalized Steam	Post-retrofit Period Month (1)	Post-retrofit GSA Steam Utility Bill (2)	Unadjusted GSA Steam Change	Post-retrofit Normalized Steam (3)	Weather Normalized Steam Change
Apr-92	$48,050	$17,469	Apr-94	$52,630	$4,580	$54,566	$37,098
May-92	$8,448	$6,185	May-94	$8,750	$302	$9,072	$2,888
Jun-92	$5,596	$5,100	Jun-94	$8,879	$3,283	$9,205	$4,106
Jul-92	$4,495	$3,364	Jul-94	$8,750	$4,255	$9,072	$5,709
Aug-92	$4,278	$3,968	Aug-94	$7,225	$2,947	$7,491	$3,523
Sep-92	$4,805	$3,813	Sep-93	$6,426	$1,621	$6,662	$2,849
Oct-92	$5,332	$6,510	Oct-93	$8,258	$2,926	$8,562	$2,052
Nov-92	$25,896	$12,307	Nov-93	$25,856	($40)	$26,807	$14,500
Dec-92	$55,633	$51,817	Dec-93	$52,917	($2,716)	$54,864	$3,047
Jan-93	$73,712	$120,544	Jan-94	$122,835	$49,123	$127,354	$6,811
Feb-93	$90,650	$136,013	Feb-94	$140,694	$50,044	$145,871	$9,858
Mar-93	$101,520	$66,991	Mar-94	$86,659	($14,861)	$89,847	$22,856
TOTAL	$428,415	$43,078		$529,879	$101,464	$549,374	$115,297

Table 7. *GSA Utility Rates Charged During the Pre-Retrofit Period on Which the Weather Normalized Savings are Calculated. The Post Retrofit Rates are Included for Comparison*

Pre-retrofit Mon-Yr	Pre-retrofit $/MMBtu CHW (1)	Pre-retrofit $/MMBtu Steam	Post-retrofit Mon-Yr (2)	Post-retrofit $/MMBtu CHW (1)	Post-retrofit $/MMBtu Steam
Apr-92	—	$15.50	Apr-94	—	$14.95
May-92	$56.75	$15.50	May-94	$25.93	$14.95
Jun-92	$41.21	$15.50	Jun-94	$25.93	$14.95
Jul-92	$28.13	$15.50	Jul-94	$25.93	$14.95
Aug-92	$30.67	$15.50	Aug-94	$25.93	$14.95
Sep-92	$25.43	$15.50	Sep-93	$26.45	$14.95
Oct-92	—	$15.50	Oct-93	—	$14.95
Nov-92	—	$15.50	Nov-93	—	$14.95
Dec-92	—	$15.50	Dec-93	—	$14.95
Jan-93	—	$15.50	Jan-94	—	$14.95
Feb-93	—	$15.50	Feb-94	—	$14.95
Mar-93	—	$15.50	Mar-94	—	$14.95
AVERAGE	$36.44	$15.50	AVERAGE	$26.03	$14.95

(1) The '-'s represent months where chilled water is not required by the building.
(2) The sequence of the months wraps around to facilitate direct monthly comparisons from the pre-retrofit period to the post-retrofit period. The pre-retrofit period includes utility bills from April 1992 through March 1993. The post-retrofit period includes utility bills from Sep. 1993 through Aug. 1994.

involved in projecting hourly daytype profiles (or hourly diversity measurements) can be substantial[31]. Therefore it is recommended that these types of measurement methods be supplemented with long-term, before-after, whole-building measurements where feasible.

(3) The thermal energy effect from a lighting retrofit can be significant and should be included in all savings measurements. In the case of the Forrestal building the lighting retrofit has led to a $115,297 (+27%) increase in the annual steam energy use. Chilled water costs decreased by approximately $218,121 (−18%). Thermal energy savings are dependent on HVAC system types and utility costs, and therefore require measurement at each site.

(4) The electricity savings resulting from the lighting retrofit amounted to a savings of $324,705 (−18%) based on the pre-retrofit utility energy and demand billing rates. The rates used in this analysis do not include local taxes, negotiated utility discounts, and power cost adjustment factors. These factors may need to be considered in other studies.

(5) Utility revenue meters can fail. Therefore it is recommended that redundant meters be used to detect the failure of utility meters and/or provide additional measurements of retrofit savings. At the Forrestal building, metering problems were experienced with all three whole-building meters (i.e., electricity, steam, and chilled water). Weekly inspection of the hourly metered

Table 8. *Comparison of Electricity, Chilled Water, and Steam Monetary Savings Due to the Lighting Retrofit. Pre-retrofit Values Shown in the Normalized Savings Represent the Post-retrofit Use Predicted by the Pre-retrofit Models*

Utility bills as actually charged:

Energy Source	Pre-retrofit	Post-retrofit	$ Change	% Change
Electricity	$1,819,147	$1,540,662	($278,485)	− 15%
CHW	$878,237	$853,923	($24,314)	− 3%
Steam	$428,415	$529,879	$101,464	24%
TOTAL	$3,125,799	$2,924,464	($201,335)	− 6%

Weather normalized savings based on pre-retrofit billing rates:

Energy Source	Pre-retrofit	Post-retrofit	$ Change	% Change
Electricity	$1,771,342	$1,446,637	($324,705)	− 18%
CHW	$1,238,797	$1,020,676	($218,121)	− 18%
Steam	$434,078	$549,374	$115,297	+ 27%
TOTAL	$3,444,217	$3,016,688	($427,529)	− 12%

data proved invaluable in finding and fixing the broken meters quickly.

(6) Independent third party measurement of savings from energy conservation retrofits is highly recommended. Such third parties should be required to use repeatable, consensus-based measurement and analysis techniques such as the DOE's NEMVP (USDOE 1996) using NIST-traceable instrumentation to assure that an accurate, affordable, scientifically-defensible analysis has been performed.

(7) There is a need for the creation of federal data centers that could be used to independently and accurately measure shared savings in federal facilities and to provide O&M feedback to building operators.

CONCLUSION

This paper has provided an overview of the lighting retrofit and presented results from the whole-building monitoring effort. Measured reductions in electricity energy use agreed within 90% of the pre-retrofit estimated savings. Peak hourly electric demand are within an average of 80% ± 10% of pre-retrofit estimated 1,300 kWh demand reductions. The chilled water savings from the reduced cooling load increased the savings by over $218,000 or 50% of the total dollar savings. The added cost of steam to make up for the heat from the old inefficient lights decreased savings by over $115,000. Clearly, the lighting retrofit at the USDOE Forrestal building is successful and is saving electricity at or near to the rates that were estimated. Furthermore, the careful study and documentation of the savings has provided a wealth of information that other federal facilities can use to help secure their own successful energy conservation projects.

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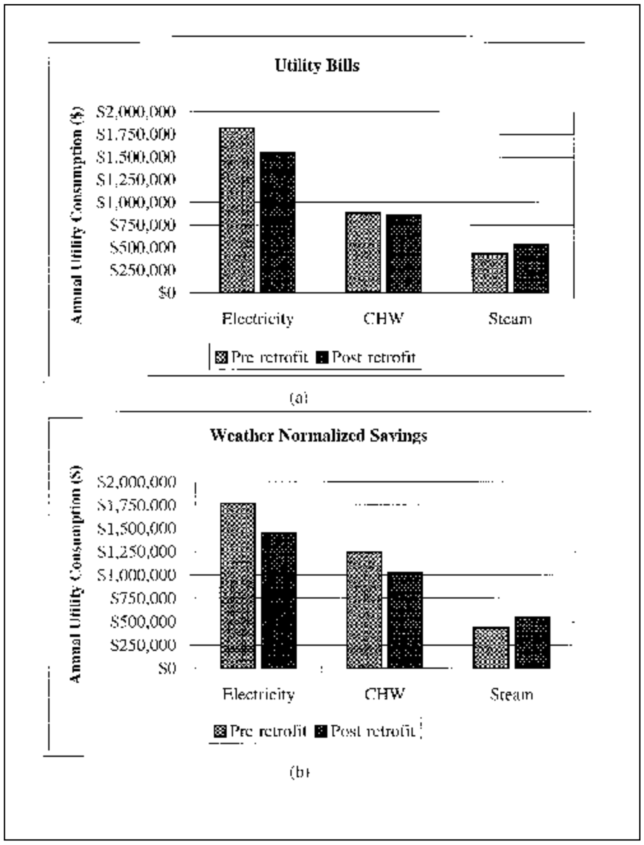
The data loggers used in the Forrestal building are manufactured by the Synergistic Controls Systems, Metairie, Louisiana. Whole-building electricity was measured by sharing

Figure 7a,b. Comparison of the Electricity, Chilled Water, and Steam Monetary Savings Due to the Lighting Retrofit. The GSA Utility Bills are Shown in Figure 7a and the Weather Normalized Savings are Shown in Figure 7b



the KYZ signal from the building's 20 + year old mechanical totalizer which is fed KYZ pulses from four 2-stator-type, mechanical watt-hour meters manufactured by General Electric. Steam was measured with an axial turbine flow meter, manufactured by the Engineering Measurements Company (EMCO) in Longmont, Colorado. Chilled water was measured with a transit-time thermal energy meter manufactured by Controlotron in Hauppauga, New York. National Weather Service (NWS) Weather data was obtained from Accuweather in State College, Pennsylvania.

ENDNOTES

1. This was also included as a provision in the 1992 National Policy Act.

2. For more information on the Texas LoanSTAR program see Verdict et al. 1990; Claridge et al. 1991, and Claridge et al. 1994. This pre-post measurement technique is also part of DOE's North American Energy Monitoring and Verification Protocol (NEMVP).

3 The Child Development Center, opened in September 1991, receives its electricity from the Forrestal building and represented roughly 134 MWh/yr in 1992. A report on the energy conserving retrofits for the CDC is available from the Energy Systems Laboratory (Haberl and Bou-Saada 1993).

4. For a more detailed look at previous metered energy analysis efforts see the paper by Haberl and Vajda (1988).

5. This slab heating is required to keep the cold from penetrating up into the fourth floor from the exposed underside below.

6. The EMCS was installed in February 1993 and controls the start-stop of the AHUs, pumps, and chilled water supplied to the AHUs.

7. This is determined by the AHU schedule on the newly installed EMCS. Previously reported hours were from 8:30 a.m. to 5:00 p.m. (Haberl and Vajda 1988).

8. This calculation uses 1,317,000 square feet which includes the underground, enclosed garages.

9. These figures use information from unadjusted, monthly utility billing data.

10. Steam is routinely shutoff on Friday nights about 8:00 p.m. and is turned on Sunday night about 12:00 midnight. This manual procedure is followed for all weekends when the ambient temperature is above about 30F (−1 C). Additional details about the steam shutoff program can be found in Haberl and Vajda (1988), and Haberl and Bou-Saada (1996).

11. Prior to 1987 the chilled water use for the Forrestal building was a negotiated amount that represented 40% of the chilled water that was produced by GSA's Central Plant. The remaining 60% was delivered to the Agriculture building which is located one block to the west of the Forrestal building. In 1987 GSA installed meters in the chilled water lines leaving the central plant and began billing according to the measured thermal energy. However, in 1987, the first year that the numbers were reported to DOE using the metered data, the thermal values that were reported were three times the monthly consumption shown, which is an impossible amount.

12. These data loggers are the commercialized version of the data loggers that DOE developed for the ELCAP project through Battelle/PNL. They are also the loggers

used in the Texas LoanSTAR program. The manufacturer's name is mentioned in the acknowledgments.

13. This original work was performed as an extension to USDOE grant DE-FG01-90CE21003 to study the use of EMCSs for performance monitoring projects (Claridge et al. 1993).

14. These measurements were taken during the period of October 23 to November 3, 1993 (Halverson et al. 1994). The data loggers used in PNL's end-use measurements are also the commercialized version of DOE's logger that was developed for the ELCAP project as indicated in the acknowledgments. A study was also performed to measure the persistence of the lighting retrofit (Chvála et al. 1995).

15. Savings to the Department of Energy also include a $1,257,409 rebate from the local utility (PEPCO 1993) which are not included in this number. The estimated electricity savings are from DOE's ''Forrestal Relighting Project Profile'' brochure.

16. These estimates are taken from a letter to Mr. Ed Liston of the EUA Cogenex company from Dr. Allan Evans of Princeton Economic Research Inc. (PERI 1993). The lower value represent those of PERI, and the higher values represent those published by EUA Cogenex. PERI's estimates are based on pollutant conversions contained in the Electric Power Annual (1990) and assume a savings of 5.2 million kWh per year. PERI's estimates do not include thermal energy savings (i.e., chilled water or steam).

17. This procedure uses a modified form of the procedure recommended by Katipamula and Haberl (1991).

18. The CV(RMSE) equations used to evaluate the models are from Thamilseran and Haberl (1995).

19. This was accomplished via modem through a commercial account with an authorized NWS weather data distributor located in State College, Pennsylvania.

20. Unfortunately, this 20-year-old mechanical pulse accumulator failed repeatedly after the retrofit was installed thereby necessitating the need for a post-retrofit model to normalize for the lost data. Therefore, the utility billing data shown in Figure 2 represent data that have been adjusted by the electric utility company and are the basis for the analysis.

21. In all cases it was assumed that GSA's readings and the local utility readings were accurate.

22. These maintenance outages include an aluminum riser replacement program, maintenance of the computer room UPS, and maintenance of the electrical vault switch gear.

23. It is estimated that this could have increased the peak whole-building electricity use by roughly 3 to 6 MW (3,200 to 6,500 tons of cooling calculated at 200–400 ft^2/ton).

24. This CV(RMSE) compares favorably with CVs reported by Kreider and Haberl (1994a, 1994b) from the application of more sophisticated models such as neural networks.

25. We use the kWh/h notation to indicate that the data were recorded using an hourly integration period, versus a 15-minute integration period.

26. Several days of bad data were removed that did not match the average profiles.

27. The utility billing data for the Forrestal building was adjusted by the local utility to account for the missing data.

28. The energy charges include an off-peak rate, an intermediate rate, and an on-peak rate. The off-peak period covers all weekdays from 12:00 a.m. to 8:00 a.m. and the entire weekend. The intermediate period covers all weekdays from 8:00 a.m. to 12:00 p.m. and 8:00 p.m. to 12:00 a.m. The on-peak period covers all weekdays from 12:00 p.m. to 8:00 p.m. The demand charges consist of a distribution charge and a production charge. The distribution rate is charged as the basic rate for demand and the production rate is charged during the summer rate schedule months effective in June through October. The figures listed in Table 1 do not include local taxes, discounts, or fuel cost adjustment factors which were found to vary dramatically from month to month.

29. The actual weather normalized cost savings for the Forrestal complex are probably higher since the $/unit cost changed slightly from the pre to post periods. If one applies the post retrofit costs to the normalized savings, the resultant monetary savings are $213,134 for CHW, −$111,206 for steam, and $337,633 for electricity for a total of $439,561, or 12.6% of the total weather normalized pre-retrofit cost.

30. The term net energy savings measurements would refer to the long term, pre-post measured savings using end-use measurements of the lighting electricity use as well as cooling and heating energy use measurements.

31. The previously reported electricity savings using portable measurements was 5.7 million kWh per year which is 57% of the annual energy use compared to 62% given in the initial audit (Halverson et al. 1994).

REFERENCES

Bou-Saada, T. 1994. *An Improved Procedure for Developing a Calibrated Hourly Simulation Model of an Electrically Heated and Cooled Commercial Building*. Masters' Thesis, Texas A&M University, College Station, TX, Energy Systems Laboratory Report No. ESL-TH-94/12-01.

Chvála, W.D., Wahlstrom, R.R., Halverson, M.A. 1995. *Persistence of Energy Savings of Lighting Retrofit Technologies at the Forrestal Building*. Battelle/PNL Report No. PNL-10543. Richland, WA: Pacific Northwest Laboratory.

Claridge, D., Haberl, J., O'Neal, D., Heffington, W., Turner, D., Tombari, C., Roberts, M., Jaeger, S. 1991. ''Improving Energy Conservation Retrofits with Measured Results.'' *ASHRAE Journal*, 33(10):14–22, (October).

Claridge, D.E., Haberl, J.S., Sparks, R., Lopez, R., Kissock, K. 1992. ''Monitored Commercial Building Energy Data: Reporting the Results.'' *ASHRAE Transactions Symposium Paper*, 98(1): 636–652.

Claridge, D., Haberl, J., Sparks, R. 1993. *Use of Energy Management and Control Systems for Performance Monitoring of Retrofit Projects, Final Summary Report*. ESL-TR-91/09/02, Texas A&M University, College Station, TX: Energy Systems Laboratory.

Claridge, D.E., Haberl, J.S., Liu, M., Houcek, J., Athar, A. 1994. ''Can You Achieve 150% of Predicted Retrofit Savings? Is it Time for Recommissioning?'' *In Proceedings of the ACEEE 1994 Summer Study on Energy Efficiency in Buildings*, 5:74–87. Washington, DC: American Council for an Energy-Efficient Economy.

Electric Power Annual. 1990. United States Department of Energy Information Agency Report No. DOE/EIA-0348(90), (January).

Haberl, J., Vajda, J. 1988. ''Use of Metered Data Analysis to Improve Building Operation and Maintenance: Early Results from two Federal Complexes.'' *In Proceedings of the ACEEE 1988 Summer Study on Energy Efficiency in Buildings*, 3:98–111. Washington, DC: American Council for an Energy-Efficient Economy.

Haberl, J., and Bou-Saada, T. 1993. *Analysis of Energy Conservation Options at the USDOE Child Development Center*. ESL-TR-93/12-04. Texas A&M University, College Station, TX, Energy Systems Laboratory.

Haberl, J., Bou-Saada, T., Vajda, E.J., Shincovich, M., D'Angelo, L.A., Harris, L. 1995. ''The U.S.D.O.E. Forrestal Building Lighting Retrofit: Preliminary Analysis of Electricity savings.'' *Proceedings of the 1995 ASME International Solar Energy Conference*, 1:295–304.

Haberl, J., and Bou-Saada, T. 1996. *The USDOE Forrestal Building Lighting Retrofit: Analysis of Electrical and Thermal Energy Savings*. ESL-TR-XX/XX-XX. Texas A&M University, College Station, TX, Energy Systems Laboratory.

Halverson, M., Schmelzer, J., Harris, L. 1993a. ''The Live Test Demonstration (LTD) of Lighting Retrofit Technologies at the DOE Forrestal Building'', *Proceedings of the 1993 AEE International Energy and Environment Congress.* Minneapolis, MN: Association of Energy Engineers.

Halverson, M. Schmelzer, J., Parker, G. 1993b. *Forrestal Building Lighting Retrofit Second Live Test Demonstration.* Battelle/PNL Report No. PNL-8540. Richland, WA: Pacific Northwest Laboratory.

Halverson, M., Stoops, J., Schmelzer, J., Chvála, W., Keller, J. and Harris, L. 1994. ''Lighting Retrofit Monitoring for the Federal Sector—Strategies and Results at the DOE Forrestal Building.'' *In Proceedings of the 1994 ACEEE Summer Study on Energy Efficiency in Buildings*, 2:137–144. Washington, DC: American Council for an Energy-Efficient Economy.

Katipamula, S., Haberl, J. 1991. ''A Methodology to Identify Diurnal Load Shapes for Non-Weather Dependent Electric End-Uses,'' *Proceedings of the 1991 ASME-JSES International Solar Energy Conference*, pp. 457–467. New York, NY: American Society of Mechanical Engineers.

Kissock, K., Xun, W., Sparks, R., Claridge, D., Mahoney, J., and Haberl, J. 1994. *EModel: Version 1.4d.* Texas A&M University System, College Station, TX: Energy Systems Laboratory.

Kreider, J. and Haberl, J. 1994a. ''Predicting Hourly Building Energy Usage: The Results of the 1993 Great Energy Predictor Shootout Identify the Most Accurate Method for Making Hourly Energy Use Predictions.'' *ASHRAE Journal* 36:72–81.

Kreider, J. and Haberl, J. 1994b. ''Predicting Hourly Building Energy Usage: The Great Energy Predictor Shootout: Overview and Discussion of Results.'' *ASHRAE Transactions Technical Paper*, 100(2).

Lopez, R., Haberl, J. 1992. ''Data Processing Routines for Monitored Building Energy Data,'' *Proceedings of the 1992 ASME/JSES/KSES Solar Energy Conference, pp.* 329–336. New York, NY: American Society of Mechanical Engineers.

Mazzucchi, R. 1992. ''End-use Profile Development From Whole-Building Data Combined with Intensive Short-term Monitoring'', *ASHRAE Transactions Symposium paper AN-92-15-5*, 98(1):1180–1184.

PEPCO 1993, Potomac Electric Power Company, 1900 Pennsylvania Ave., N.W., Washington, DC, 20068-0001.

PERI 1993. Environmental impact values were extracted from a letter to Mr. Edward Liston, of the EUA Cogenex Corporation dated June 11, 1993 from Dr. Allan R. Evans, Princeton Economic Research Inc., 12300 Twinbrook Parkway, Suite 650, Rockville, MD, 20852.

Thamilseran, S., Haberl, J. 1995. ''A Bin Method for Calculating Energy Conservation Retrofits Savings in Commercial Buildings.'' *Proceedings of the 1995 ASME/JSME/JSES International Solar Energy Conference*, 1:111–123. Lahaina, Maui, HI.

United States Department of Energy. 1996. ''North American Energy Measurement and Verification Protocol,'' United States Department of Energy, Federal Energy Management Program.

Verdict, M., Haberl, J., Claridge, D., O'Neal, D., Heffington, W., Turner, D. 1990. ''The Texas LoanSTAR Monitoring and Analysis Program: Overview.'' *In Proceedings of the 1990 ACEEE Summer Study on Energy Efficiency in Buildings*, 7:261–271. Washington, DC: American Council for an Energy-Efficient Economy.