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THE U.S.D.O.E. FORRESTAL BUILDING LIGHTING RETROFIT: PRELIMINARY ANALYSIS OF ELECTRICITY SAVINGS

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ABSTRACT

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.

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. Estimates of the electricity savings were $399,058 per year, or $1,350,386 over a seven year period[2]. 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[3].

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[4]. 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 has continued through November of 1994, fifteen months after the September 1993 retrofit completion date.

This paper provides an overview of the lighting retrofit and presents preliminary results from the whole-building monitoring effort that show that the measured gross electricity savings from the lighting retrofit performed within 90% of the estimated savings, and that measured reductions in monthly peak hourly electric demand performed within 68% to 91% of estimated demand reductions[5].

INTRODUCTION

The USDOE Forrestal Complex

The James Forrestal building, located at 1000 Independence Avenue, Washington, D.C., is comprised of interconnected north, south and west wings, and a newly built Child Development Center[6] directly south of the cafeteria. The north wing of the Forrestal complex is elevated 3 stories above Independence Avenue and is comprised mostly of executive offices. Tenth street passes directly underneath the north building and separates the south and west buildings. The south building is connected to the north building with four aerial walkways and to the west building with corridors underneath

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

[2] Savings to the Department of Energy also include a $1,257,409 rebate from the local utility (PEPCo 1993). The estimated electricity savings are from DOE's "Forrestal Relighting Project Profile" brochure.

[3] 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).

[4] For more information on the Texas LoanSTAR program see Verdict et al. 1990; Claridge et al. 1991).

[5] Detailed information regarding the retrofits savings can be found in the report by Haberl and Bou Saada (1994).

[6] The Child Development Center, opened in September 1991, receives its electricity from the Forrestal building which represents roughly 134 MWh/yr in 1992.

Tenth Street. The south building surrounds an interior courtyard and contains office space, several small cafeterias and an employee gym. The west building is comprised mostly of a cafeteria and related services. In September of 1991 a USDOE Child Development Center was completed and opened for use by DOE staff. This 8,100 ft^2 (752.5 m^2) facility is located adjacent to the DOE cafeteria on the south side[7].

The Forrestal building is primarily constructed of precast and cast-in-place concrete. Precast recessed window units, encasing 1/4 inch (0.64 cm) plate glass, are the most prominent feature of the envelope. The main entrance to the complex is located below the north building through automated sliding doors that lead into a glazed vestibule.

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. A detailed accounting of the building is contained in the JRB reports (1981). In general, the exterior envelope of the building has minimal insulation. A large portion of the building representing 668,000 ft^2 (62,059 m^2) is actually below grade and connects the north, south and west buildings underneath Tenth Street. Roofs throughout the building are high mass composite construction with 2 inch (5.1 cm) rigid insulation.

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 at 12th and C Streets. 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 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[8].

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[9], 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[10] a state-of-the-art computerized Energy Management and Controls System was installed that now performs the basic functions that the previous manual system performed. Normal business hours[11] for the 4,400 employees are from 6:30 a.m. to 6:30 p.m., Monday through Friday.

Energy conservation efforts at the Forrestal building (1986-1994)

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)[12] . These costs were broken down as follows, $3,141 for natural gas, $452,298 for steam, $927,473 for chilled water and $1,672,045 for electricity. Figure 1 provides a summary of the utility costs from FY 1987/88 through FY 1993/94. Figure 2a shows the monthly electricity use, and peak electric demand. Figure 2b shows the chilled water and steam use from utility billing records[13]. Prior to the lighting retrofit the average monthly electricity use for the Forrestal building increased by roughly 400 MWh 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.

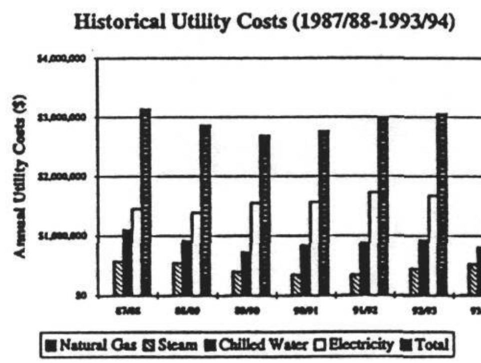


FIGURE 1: HISTORICAL UTILITY COSTS 1987 - 1994. THIS BAR GRAPH SHOWS THE HISTORICAL UTILITY COSTS FROM FY 19887/88 THROUGH FY 1993/94. THE FORRESTAL COMPLEX CONSUMES NATURAL GAS, STEAM, CHILLED WATER, ELECTRICITY, AND POTABLE WATER.

[7] A report on the energy conserving retrofits for the CDC is available from the Energy Systems Laboratory (Haberl and Bou-Saada 1993).

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

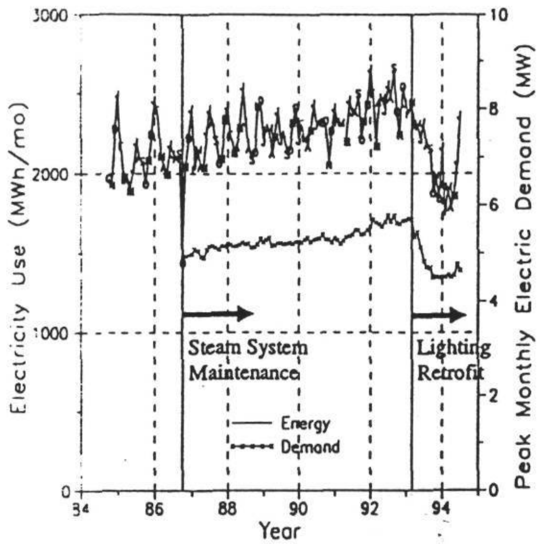
[9] This slab heating is required to keep the cold from penetrating up into the fourth floor from the exposed underside below.

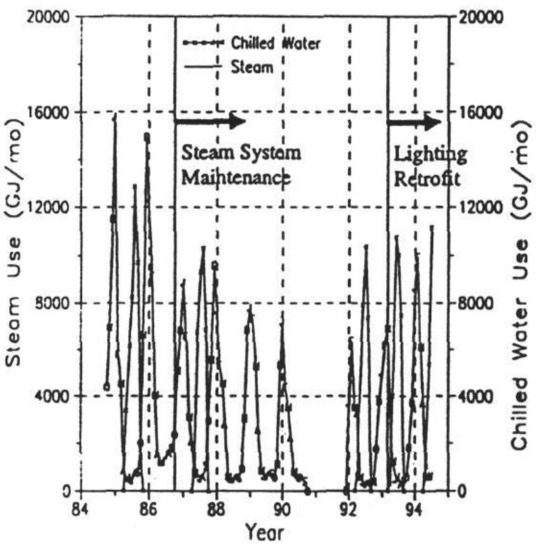
[10] The EMCS was installed in February 1993 and controls the start-stop of the AHUs, pumps, and chilled water supply to the AHUs.

[11] 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).

[12] This calculation uses 1,317,000 square feet which includes the garage.

[13] Both figures use information from unadjusted, monthly utility billing data.





FIGURES 2A,B: MONTHLY UTILITY BILLING DATA FOR THE DOE FORRESTAL COMPLEX. THE UPPER GRAPH SHOWS THE MONTHLY ELECTRICITY USE AND PEAK ELECTRIC DEMAND FOR THE FORRESTAL BUILDING FROM 1984 THROUGH JUNE OF 1994. THE LOWER GRAPH SHOWS THE MONTHLY STEAM AND CHILLED WATER USE FROM OCTOBER 1984 THROUGH JUNE OF 1994.

In Figure 2b 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[14]. This reduction in steam use resulted in an annual savings of over $250,000 per year and, due to the diligence of the Forrestal staff, has persisted for eight years since it was first initiated during the winter of 1986/87 which amounts to a total savings in excess of $2,000,000.

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[15]. The monthly chilled water consumption for the Forrestal building increased during this period. This is most likely due to the increased cooling load from the large number of personal computers that were added to the Forrestal building's electrical load[16].

Overview of the 37,000 fixture lighting retrofit

In 1989 a Shared Energy Savings lighting retrofit project was proposed for 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[17] electrical data loggers and whole-building data from the local utility's 15-minute electricity demand data (Mazzucchi 1992). Lighting electricity represented 33% of the whole building electricity consumption. The 24-hour end-use lighting profiles of the 277-volt fluorescent lighting loads[18] were then used by the DOE to

[14] 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 (1994).

[15] The 21% increase represents a preliminary estimate based on the comparison of unadjusted GSA utility billing data for the period 9/92-5/93 versus 9/93-5/94.

[16] 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. Therefore a 1/3 adjustment factor has been applied to allow for the graphical presentation shown in Figure 2b.

[17] 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.

[18] This represented a significant amount of work because the 131 panels that feed the 277-volt fluorescent lighting are spread throughout the building on various floors inside of electrical risers that feed upward from the five main electrical vaults located below grade. This is further complicated by the fact that there are four 13.2 kV feeders to the five electrical vaults (switchboards) where the electricity is transformed to 460/265V, three phase, four wire service.

establish engineering estimates of the weekday-weekend baseline lighting loads which served as the basis for the RFP.

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[19].

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, weekday-weekend post-retrofit lighting profiles [20]. Whole-building electricity and thermal energy use measurements continued through August 1994[21].

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, it is all to easy to find projects that failed to live up to expectations after measurements are made. 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 take the steps that are necessary to accurately measure the savings.

To demonstrate this point unadjusted utility costs for the Forrestal complex are shown from August through July for 1992/93 and 1993/94 with the difference plotted against the negotiated savings[22] as shown in Figure 3. Clearly, had the Forrestal staff only been looking at the monthly difference between the two years they would have had cause for alarm because none of the months showed savings that equaled or exceeded the $33,256 which represents 1/12 of the projected $399,058 annual savings. It will be shown that the electricity savings (i.e., kWh) did indeed occur as estimated when a more accurate evaluation is conducted that adjusts for several confounding factors.

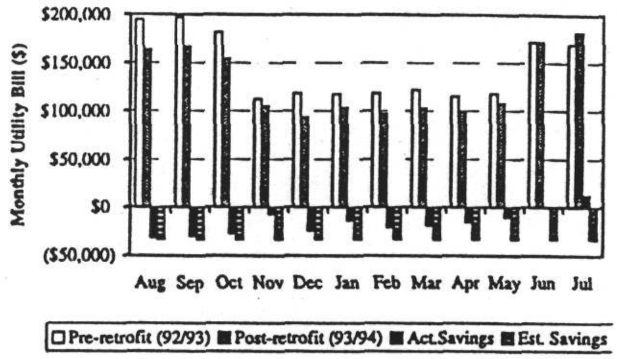


FIGURE 3: COMPARISON OF FY 1992/93, FY 1993/94 UTILITY BILLING DATA AND NEGOTIATED ELECTRICITY SAVINGS FOR THE LIGHTING RETROFIT. THIS PLOT SHOWS THE FY 1992/93 UTILITY BILLING DATA, THE FY 1993/94 UTILITY BILLING DATA AND COMPARES THE UNADJUSTED UTILITY COSTS FOR THE TWO PERIODS AGAINST THE NEGOTIATED ELECTRICITY SAVINGS.

METHODOLOGY

Measuring the electricity and thermal energy savings with whole-building hourly data

The methodology that has been applied to calculate the gross, whole-building electricity savings from the lighting retrofit uses a basic before-after analysis of the whole-building electricity use. This methodology separately calculates weather-dependent and non-weather-dependent energy use by developing empirical baseline models that are consistent with the known loads on a given channel. This paper reports on the non-weather-dependent electricity savings from the lighting retrofit. Weather-dependent thermal savings will be reported as well (Haberl and Bou-Saada 1994).

In the non-weather-dependent procedure a baseline statistical model of the 1992 non-weather dependent energy use was calculated using 24-hour, weekday-weekend hourly profiles. The hourly electricity savings were then calculated by forecasting the 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). The general form for this procedure is as follows:

$$E_{save,tot} = \sum_{i=1}^{n} N_i \sum_{j=1}^{m} \left(E_{pre_{i,j}} - E_{post_{i,j}} \right) \qquad (1)$$

[19] 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).

[20] 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 and in the whole-buildings measurements are the commercialized version of DOE's logger that was developed for the ELCAP project as indicated in the acknowledgments.

[21] These are the basis for the current paper.

[22] To make this simple comparison the basic utility billing data was used. This includes the following charges: discount charge, fuel adjustment, misc. adjustments, kWh charges, and kW charges. The local utility's "previous balance adjustments" credits were not included in Figure 3.

where

$E_{pre_{i,j}}$ = the pre-retrofit bin model predicted average hourly electricity use during hour (j) of daytype (i) in the post retrofit period.

$E_{post_{i,j}}$ = the post-retrofit bin model predicted average hourly electricity use during hour (j) of daytype (i) in the post retrofit period.

N_i = the number of days of daytype (I) in the post-retrofit period.

i = distinct day type varying from i = 1 (all seven days per week the same), to i = 365 (every day of the year different).

j = 1 to 24 hours in each day.

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[23] that attempts to select the fewest number of 24-hour profiles that 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) [24].

Applying the 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[25]. Whole-building electricity use was recorded with a single KYZ pulse from a shared signal from the utility's pulse accumulator that collects the pulses from the four 13.2 kV electricity feeders into the building[26] in the A Vault located underneath the north building. Submetered electricity was also measured for selected motor control centers (MCC), elevator panels, lights and receptacles, and for the Child Development Center (i.e., labeled as "Daycare") in both the A and C vaults. Additional monitoring was also conducted on the CDC using a separately installed logger installed in 1991 in order to determine the effectiveness of the energy conservation measures that had been designed (Haberl and Bou-Saada 1993).

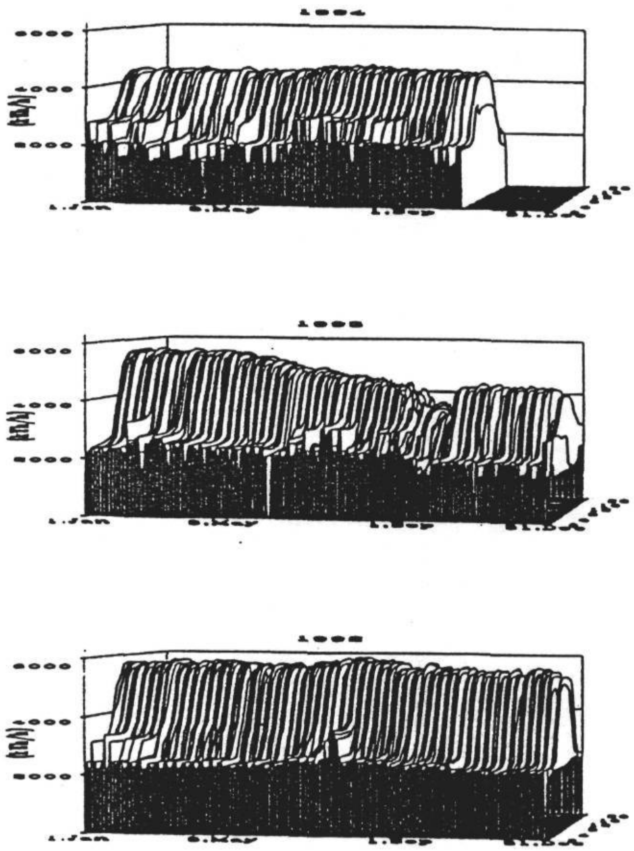
[23] This procedure uses a modified form of the procedure recommended by Katipamula and Haberl (1991).

[24] The CV(RMSE) equations used to evaluate the models are listed in the paper by Thamilseran and Haberl (1995).

[25] This was accomplished via modem through a commercial account with an authorized NWS weather data distributor.

[26] 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 3 represent data that have been adjusted by the electric utility company.

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 and supply and return temperatures. Steam measurements were taken by an insertion-type axial turbine steam meter located in the building's 250 lb (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[27]. Steam meter calibrations were performed periodically by the GSA. Data from three loggers were collected weekly and plotted and inspected visually for errors using automatic routines developed as part of the LoanSTAR program (Lopez and Haberl 1992).



FIGURES 4A,B,C: 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 NOVEMBER 1994 DISPLAYED AS AN HOURLY 3-D TIME SERIES PLOT.

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

RESULTS

General

Figure 4 shows the hourly whole-building electricity data collected from the site for the period January 1992 through October 1994 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 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. Prior to the retrofit, during extreme summer conditions, this was necessary 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 in the cooling coils within air-handling units.

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 by 700 kW 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 has continued to fail periodically throughout the remainder of the post-retrofit monitoring period. This problem was further compounded by maintenance power outages[28] that were initiated in 1993 and continued through 1994. Both of these problems contributed to abnormal usage profiles that necessitated the use of an empirical post-retrofit model to measure the lighting retrofit savings.

Development of the 24-hour, pre-post, weekday-weekend profiles

One of the most prominent features of the 1992 baseline data shown in Figure 4 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[29]. This lack of any weather dependency meant that the whole-building electricity use could be accurately modeled with non-weather dependent 24-hour daytype profiles using the method that has been previously described.

Using the methodology developed by Thamilseran & 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 5, including: a weekday profile (i.e., the upper plot), a winter weekend profile (middle plot), and a summer weekend profile (lower plot). 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[30]. Furthermore, an RMSE of 208.75 kWh/h[31] indicated that the model was capable of measuring the estimated 1,300 kW demand savings.

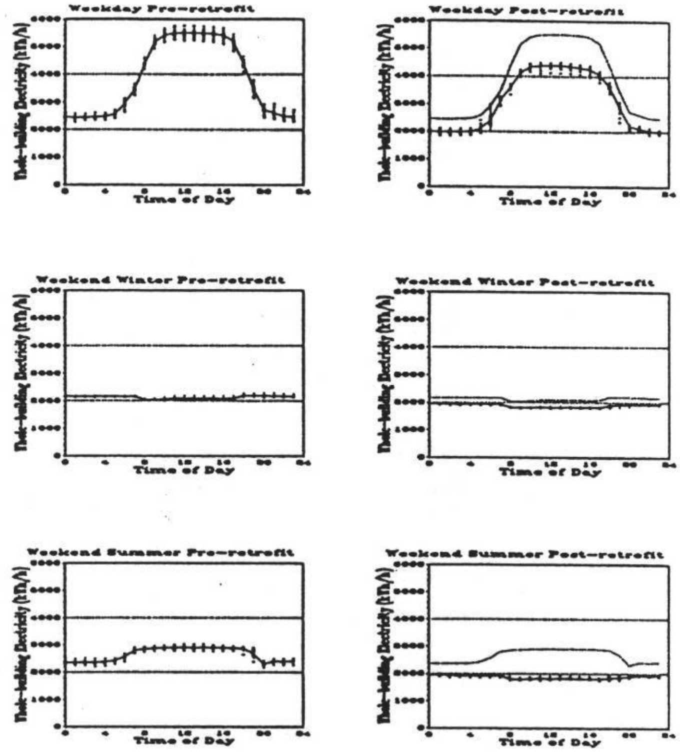


FIGURE 5A,B,C: WHOLE-BUILDING PRE-POST, WEEKDAY-WEEKEND 24-HOUR DAYTYPE PROFILES FOR THE DOE FORRESTAL COMPLEX. THESE FIGURES SHOW THE 24 HOUR STATISTICAL DAYTYPE PROFILES OF THE WHOLE-BUILDING ELECTRICITY USE FOR THREE DAYTYPES (WEEKDAY, WEEKEND-WINTER, WEEKEND-SUMMER) DURING PRE-RETROFIT AND POST-RETROFIT PERIODS.

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

[29] It is estimated that this could have increased the peak whole-building electricity use by roughly 4 to 6 MW (4,000 to 6,000 tons of cooling calculated at 200-400 ft^2/ton).

[30] This CV(RMSE) compares favorably with CVs reported by Kreider and Haberl (1994) from the application of more sophisticated models such as neural networks.

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

The goodness of fit of the three daytypes to the pre and post-retrofit data can be easily seen in Figures 6 and 7. In Figures 6 and 7 the whole-building electricity use for 1992 is shown in the upper plot and the predicted electricity use using the daytype profiles is shown in the second plot. In the third and fourth plots positive-only residuals have been plotted to

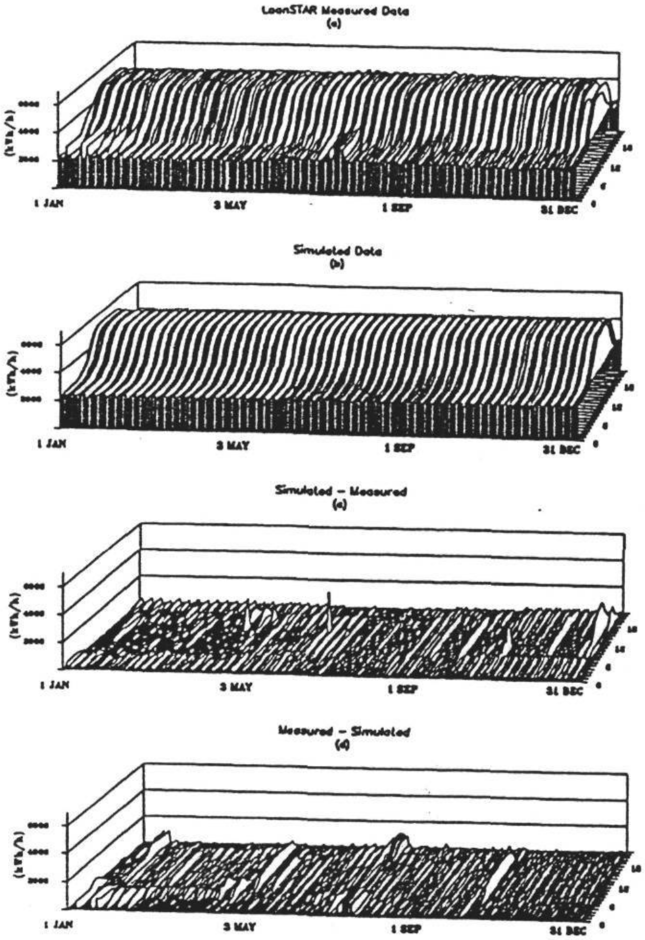

FIGURE 6A,B,C,D: COMPARATIVE WHOLE-BUILDING PRE-RETROFIT ELECTRICITY USE FOR THE DOE FORRESTAL COMPLEX (THREE DAYTYPES) FOR 1992. THESE COMPARATIVE 3-D TIME SERIES PLOTS SHOW THE MEASURED WHOLE-BUILDING PRE-RETROFIT ELECTRICITY USE (UPPER PLOT), ELECTRICITY USE PREDICTED BY THE DAYTYPE (SECOND PLOT), AND RESIDUAL PLOTS THAT SHOW THE HOURLY SIMULATED MINUS MEASURED ELECTRICITY USE (THIRD PLOT), AND MEASURED MINUS SIMULATED ELECTRICITY USE (LOWER PLOT).

show periods when the simulated electricity use was over-predicting the measured electricity use (simulated-measured -- the middle plot), or under-predicting (measured-simulated -- the lower plot) [32].

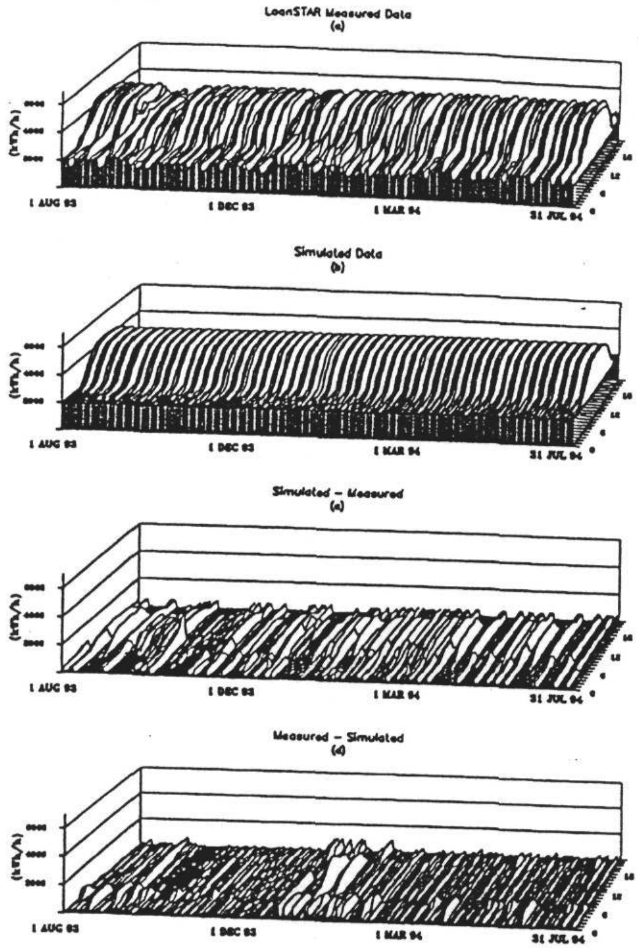

FIGURE 7A,B,C,D: COMPARATIVE WHOLE-BUILDING POST-RETROFIT ELECTRICITY USE FOR THE DOE FORRESTAL COMPLEX FOR THE PERIOD AUGUST 1993 THROUGH JULY 1994.

Figure 7 shows the post-retrofit measured data, the 3-daytype, post-retrofit model and residual plots for the period August 1993 through July 1994. 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% in Table 1. 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 7. The other periods when the meter failed, or power consumption was below normal due to maintenance[33] are evident as positive ridges in the third plot and are scattered throughout the remainder of the monitoring

[32] The use of these 3-D residual plots has previously been shown to be useful in Haberl and Vajda (1988), Haberl and Komor (1990b), and Haberl et al. (1993).

[33] This is referring to the aluminum riser replacement, computer UPS maintenance, and electrical vault switchgear maintenance.

period. The data appearing in the fourth plot represent periods when the measured electricity use was greater than the statistically predicted use.

TABLE 1: EMPIRICAL MODEL PARAMETERS. THIS TABLE COMPARES HOW WELL THE 24-HOUR DAYTYPE MODELS PREDICTED THE ENERGY USE DURING THE PERIOD SHOWN. IN BOTH THE PRE-RETROFIT AND POST-RETROFIT PERIODS THREE MODELS WERE USED, INCLUDING: WEEKDAY, WINTER WEEKEND AND SUMMER WEEKEND MODELS.

Period	CV(RMSE)	RMSE	MBE
	%	(kWh/h)	%
1/1/92 to 12/31/92	6.22	208.75	-0.61
10/1/93 to 11/30/93	5.66	152.6	-0.17
8/1/93 to 7/31/94	14.67	379.8	3.54

TABLE 2: SAVINGS COMPARISONS. IN THIS TABLE UTILITY BILLING DATA FOR AUGUST 1993 THROUGH JUNE 1994, AND JANUARY TO DECEMBER 1992 ARE COMPARED AGAINST THE SIMULATED SAVINGS FOR THE SAME CALENDAR MONTHS.

	Aug. 1993 to Jun. 1994		Jan. to Dec. 1992				
		Utility		Utility	Utility	Simulated	Utility
	Dates	Billed (kWh)	Dates	Billed (kWh)	Difference (kWh)	Difference (kWh)	Difference (kW)
Aug	7/24-8/23	2,171,109	7/23-8/21	2,462,147	291,038	540,223	959.0
Sep	8/24-9/22	2,150,546	8/22-9/22	2,655,715	505,169	522,009	1,097.3
Oct	9/23-10/21	1,872,685	9/23-10/22	2,380,244	507,559	421,826	1,143.4
Nov	10/22-11/22	1,983,824	10/23-11/20	2,235,887	252,063	427,802	1,100.2
Dec	11/23-12/22	1,838,133	11/21-12/23	2,534,937	696,804	404,412	1,169.8
Jan	12/23-1/25	2,165,273	12/23-1/27	2,654,375	489,102	476,914	1,033.9
Feb	1/26-2/22	1,731,429	1/28-2/27	2,491,367	759,938	472,599	1,186.6
Mar	2/23-3/25	1,913,079	2/28-3/25	2,166,693	253,614	442,892	1,085.8
Apr	3/26-4/25	1,780,789	3/26-4/24	2,441,166	660,377	421,464	1,091.5
May	4/26-5/24	1,858,445	4/25-5/26	2,469,551	611,106	408,788	996.4
Jun	5/25-6/23	2,078,466	5/27-6/24	2,387,796	309,330	486,381	878.4
Jul	6/24-7/25	2,356,860	6/25-7/23	2,552,896	196,036	541,385	1,134.7
12 Month Total		23,900,638		29,432,754	5,532,136	5,566,695	-

In order to compensate for the bad data in the 1993/94 post-retrofit period a post-retrofit model was developed from representative data[34] from the period immediately after the retrofit of October 1, 1993 to November 30, 1993. This post-retrofit model consisted of one weekday profile and winter-summer weekend profiles which can be seen in the right hand plots in Figure 5. The CV(RMSE) of 5.66% in Table 1 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 are tabulated in Table 2 and compared against the savings calculated by subtracting adjusted utility bills[35]. 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 5.566 million kWh which is about 9.5% below the estimated savings of 6.149 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 favorable to the estimated 1,300 kW demand reduction estimate. 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 measurement method.

[34] Several days of bad data were removed that did not match the average profiles. Additional information regarding the removal data can be found int he final report by Haberl and Bou Saada (1994).

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

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[36] of electricity savings from lighting savings when the size of the savings is expected to be above the inherent noise of the measurement method. This paper has focused on the use of pre-post hourly whole-building electricity measurements that could easily be obtained for any building using the existing revenue meters[37].

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.

2. Utility revenue meters can fail. Therefore it is recommended that redundant meters be used to either 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 metered data proved invaluable in finding and fixing the broken meters quickly.

3. The thermal energy effect from a lighting retrofit can be significant and should be included in the savings measurement. In the case of the Forrestal building the lighting retrofit has lead to an estimated[38] $80,000 (+20%) increase in the annual steam energy use. Chilled water costs are expected to decrease by a similar amount. Thermal energy savings are dependent on HVAC system types and utility costs, and therefore require measurement at each site.

4. 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 involved in projecting hourly daytype profiles (or hourly diversity measurements) can be significant[39]. Therefore it is recommended that these types of measurement methods be supplemented with long-term, before-after, whole-building measurements where feasible.

5. 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 using NIST-traceable instrumentation to assure that an accurate, affordable, scientifically-defensible analysis has been performed.

6. The results of this study indicate that there is a need for the creation of federal data centers that could be used to 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 that showed that the measured gross electricity savings from the lighting retrofit agreed within 90% of the estimated savings. Measured reductions in peak hourly electric demand are within 68 to 91% of estimated 1,300 kWh demand reductions. 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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[36] The term net energy savings measurements would refer to the long term, pre-post measured savings using lighting end-use measurements.

[37] Using the methods developed in the Texas LoanSTAR program it is estimated that whole-building electric and thermal metering can be installed and maintained and an analysis performed for about 5 to 10% of the retrofit costs, or about 3 to 5% of the annual utility bill.

[38] This is a preliminary estimate based on a comparison of unadjusted utility billing data.

[39] The previously reported electricity savings using portable measurements was 5 million kWh per year (Halverson et al. 1994).

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The data loggers used in the Forrestal building are manufactured by the Synergistics Controls Systems, Metairie, Louisiana. The data logger in the CDC is a Campbell Scientific 21X data logger manufactured by Campbell Scientific in Logan, Utah. Whole-building electricity was measured by sharing 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. Weather data was obtained from Accuweather in State College, PA.