Energy Benchmarking In Commercial Office Buildings

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Office buildings must be improved to make major gains in reducing U.S. building energy use. Energy benchmarking offers initial building energy performance assessment without rigorous evaluation. ''Seeing'' that building energy use is excessive, is the first step to change. Energy benchmarks based on the Commercial Buildings Energy Consumption Survey (CBECS) are investigated in support of the U.S. Department of Energy's Energy Partnerships program.

The 1992 CBECS database is used to develop distributions of electric energy use intensities (EUIs) in office buildings for the nine U.S. census divisions. Individual building EUIs can be compared to these distributions as an indication of building energy performance. Median EUIs are less sensitive to individual building EUIs when groups of buildings are benchmarked to one another or to census division statistics. Excessive individual EUIs (exceeding 100 kWh/sqft) strongly influence averages in the CBECS database and in local sampling. Based on limited comparisons, however, both census division average and median EUIs are not reliable indicators for more localized EUIs.

Stepwise linear regression modeling was used to identify the strongest determinants of office building energy use intensities. Statistically significant relations were found between building EUIs and several CBECS variables. Beyond floor area, the most dominant variables were the number of workers, number of personal computers, owner-occupancy, operating hours, and the presence of an economizer or chiller. The resulting performance models can be used to predict EUIs that are much better benchmarks than simple census division statistics.

INTRODUCTION

Existing commercial buildings must be improved to make major gains in controlling or reducing U.S. building energy use. Office buildings, the largest energy user of the 14 principal building activities identified in the Commercial Buildings Energy Consumption Survey (CBECS) (EIA 1995), are an excellent place to start.

One method of assessing energy savings potential without rigorous evaluation is by benchmarking or comparison to similar buildings. ''Seeing'' that a building uses more energy than 80 or 90% of similar buildings can be a convincing indicator for building improvements. The problem with benchmarks is that few exist, and for those that do, reliability is uncertain. This work was performed to support the US Department of Energy's Energy Partnerships program, which is interested in simple tools or benchmarks based on the performance of actual buildings that can be used to judge energy performance.

BACKGROUND

Energy use intensity (EUI) reflects a rate of energy use and is a type of energy benchmark that is widely used in building energy analysis. Expressed as kWh/sqft, it is the preferred unit of analysis for commercial end-use demand forecasting (Eto 1990). For commercial buildings, the EUI is also commonly expressed in units of Btu/sqft. EUIs are an attempt to normalize energy use relative to a primary determinant of energy use (building floor area in this case) such that the energy use of many buildings are comparable. By normalizing out primary determinants, it is hoped that wide differences between building EUIs will be indicators of inefficient buildings or systems where improvements can be made.

EUIs are almost a standard unit of measurement for energy analysis and have been studied for use as whole-buildings energy design targets (Crawley et al. 1987). The development of EUIs has been approached in many ways including localized sampling by utilities, prototype analysis, performance modeling, load shape estimation, through concensus estimates, and wide-scale national sampling (Eto 1990, Fireovid & Misuriello 1990, Akbari et al. 1994, Crawley et al. 1987, EIA 1995). While normalized for a primary determinant of building energy use (floor area), EUIs continue to vary widely and thus, are uncertain benchmarks as indicators of the performance of an individual building.

SCOPE

This work was performed to see if CBECS data could be used to develop simple statistics or models that could be reliable benchmarks or estimators of office building electricity use. Specifically, the distributions of CBECS electricity use data and models developed from it were examined. Results such as these are desired in order to provide a way to estimate electricity use for benchmarking to other similar buildings. The work was also performed to identify the primary determinants of energy use in office buildings from CBECS building statistics.

APPROACH

Energy performance and building characteristics data for office buildings were extracted from the CBECS database and used for this analysis. Summary statistics were produced that characterize how the electricity use per square foot in office buildings is distributed. EUI ranges were characterized for each of the nine census divisions identified in the CBECS database. These results are intended to give the building owner/manager EUI distributions that can be used to pinpoint how their building compares to others in their area.

Screening criteria were applied to produce a more reliable working dataset. These criteria excluded buildings where imputed values were commonly used and where square footage was reported as a weighted average. The details of the area exclusion and the justification follow.

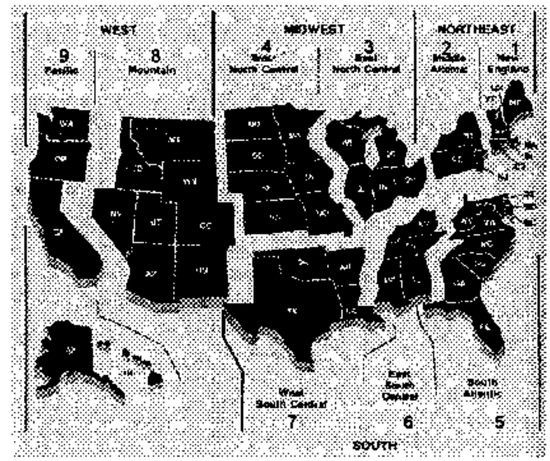
The final portion of this work applied stepwise least-squares linear regression modeling to CBECS data to identify the primary determinants of electricity use in office buildings. Determinants were limited to those available in the CBECS database and are thus restricted to their definitions as defined in CBECS documentation. The dominant and most common building characteristics that drive office building energy use were identified for each census division. These were used to develop predictive models for estimating the electric energy use of office buildings.

THE CBECS DATABASE

The 1992 Commercial Buildings Energy Consumption Survey (CBECS) contains energy consumption, energy expenditure, and energy-related building characteristics for 6,751 commercial buildings. All fifty states and the District of Columbia are represented. U.S. office buildings comprise 1443 buildings in this database. The most detail on building location is one of nine census divisions in the U.S. as shown in Figure 1.

All buildings in the database have over 1,000 square feet of floor area. Except for buildings larger than one million square feet, reported floor areas have been rounded within square footage categories. As a result, a maximum error of 10% can occur in reported floor areas. Similar rounding and maximum percentage errors occur in the reported number of workers when below 5000.

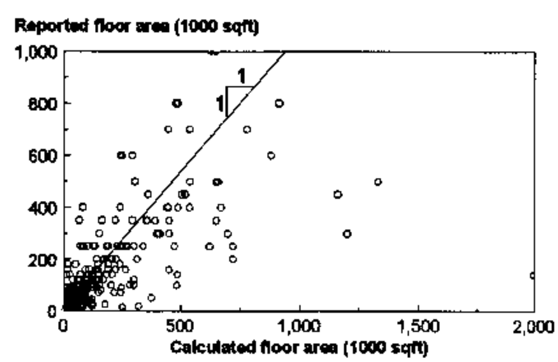
Figure 1. *The Nine U.S. Census Divisions as Defined in the CBECS*



Source: Adapted from EIA (1995) 322.

CBECS building characteristics data were collected through personal interviews with building owners, managers, and tenants. As a result, their accuracy is dependent on how well those interviewed knew their building(s). This can be a problem as discovered when calculated floor areas (based on reported building length and width at ground level, and the number of floors) are compared to reported floor areas for square and rectangular buildings. Figure 2 shows that many calculated floor areas are much smaller than reported floor areas. Unless upper floors are larger than ground-level

Figure 2. *Reported Floor Area Versus Floor Area Calculated from Reported Ground-Level Building Length and Width, and Number of Floors for Square and Rectangular Buildings*



floors, which is rare in buildings, calculated areas should match or exceed reported areas. Calculated areas that contradict this occur for many buildings. Errors in length and width data are most suspected because strong correlations were found between electricity use and reported floor areas.

RESULTS

The CBECS data set contains weighting factors which attempt to weight each building in proportion to the number of buildings in the U.S. that the specific building represents. These weighting factors were not applied for this analysis. Thus, each building in the database represents a single building in the analysis. This was done to keep the analysis simplified and also, because of the uncertainty that these specific weighting factors would produce appropriate representations since individual building characteristics like those resulting from this analysis can vary so much from building to building. In addition, the analysis was done on each census division which breaks the CBECS data set into nine smaller data sets. Entirely different weighting factors could be needed to appropriately represent this case.

This analysis uses 1358 of the 1443 office buildings in the CBECS data set. Buildings were excluded from the analysis by area screening and due to missing values in the CBECS database. An area screening criteria of 1 million square feet, the most important factor, removed 59 buildings from the analysis. The number of personal computers category variable, PCTRMC, forced the loss of an additional 22 buildings due to missing values but was retained in the analysis due to its strong correlation to electricity use. Two other variables with missing values caused the remaining exclusions (ELCNS5–1 exclusion; NWKER = 0–3 exclusions). Six percent of the CBECS office buildings were excluded due to these factors. The 1358 remaining buildings were distributed across census divisions as summarized in Table 1.

Instead of actual floor area, the CBECS provides a weighted average for buildings larger than 1,000,000 sqft (4% of the sample). The impact of weighted averages on the data distribution for census division 7 can be seen in Figure 3. Buildings exceeding 1,000,000 square feet were removed to prevent weighted area averages from adversely biasing EUI results and regression-based models. Weighted floor area could easily be one-half of the actual floor area of an individual building. Accordingly, an EUI calculated for this case would be twice the actual EUI. Although the CBECS reports similar weighted averages for the number of workers above 5000, the area screening criteria removed these large buildings, preventing them from creating a second similar problem.

EUI Distributions

Office building EUIs were calculated from electric consumption and floor areas reported in the CBECS. Median and average EUIs are given by census division in Table 1. Note that there are sizeable differences between medians and averages within most census divisions. This occurs because EUI distributions are skewed toward higher EUIs. In the CBECS database, there are office buildings which have unreasonably high and low values for electric EUIs. The excessively high

Figure 3. *Impact of Area-Weighted Averages Used Above 1,000,000 Square Feet on the Data Distribution*

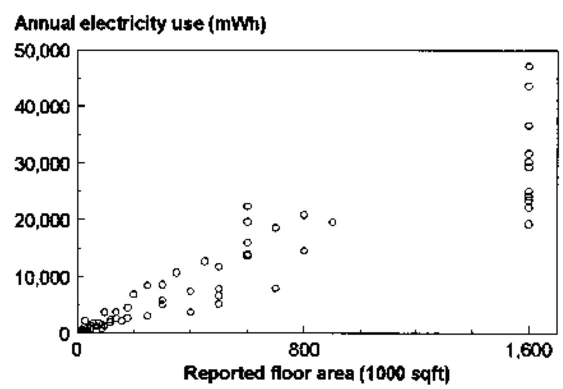


Table 1. *Number of Buildings and Electric Energy Use per Square Foot of Floor Area by Census Division*

Census division	1	2	3	4	5	6	7	8	9
No. of buildings	76	190	212	81	234	86	142	83	254
Median	11.6	12.9	11.0	12.3	16.5	18.3	15.0	14.9	13.3
Average	15.1	16.3	16.6	16.9	20.8	24.5	17.2	20.7	17.0

values are of most concern because the skewed distribution allows a small number of them to substantially increase average EUIs. For all CBECS office buildings, the upper 1% of EUIs ranged from 107 to 198 kWh/sqft. These 1% account for 6% of the average EUI for all buildings.

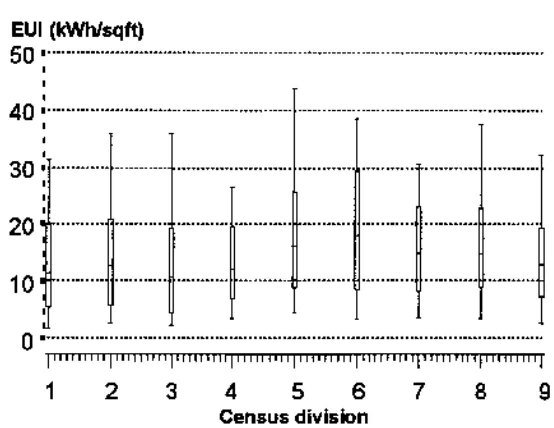
While EUIs above 100 kWh/sqft are more typical of food service buildings, they do occur occasionally for office buildings. In two small data sets provided by utilities in South Carolina (31 buildings) and Montana (27 buildings), one building (less than 2%) had an EUI of 110 kWh/sqft. All other building EUIs were below 50 kWh/sqft. This one building caused the average for the combined data sets to be 14.5 kWh/sqft versus 12.9 kWh/sqft without it, an 11% difference. The impact to the individual state average where it occurred was from 15.4 to 18.4 kWh/sqft, a 20% increase.

The problem of a few excessively high EUIs significantly increasing an average EUI occurred in some census divisions. Averages should therefore be used with caution. In contrast, buildings with excessive EUIs had little impact on EUI medians.

The median EUI for all office buildings was 13.8 kWh/sf. Median EUIs ranged from 11 kWh/sf for census division 3, the Great Lakes area, to 18.3 kWh/sf for census division 6, the East South-Central states. This spread is less than that resulting for averages. In this data set of 1358 office buildings, 75% of all buildings use less than 22.2 kWh/sf, 50% use less than 13.8 kWh/sf, and 25% use less than 7.0 kWh/sf.

EUI distributions were examined to determine values corresponding to five percentiles that bracket EUI values within a census division. The box plots in Figure 4 show the 10, 25, 50, 75, and 90th percentiles by census division. Note that the distances from the median to the 90th percentile is greater (and often much greater) than the distances from the median to the 10th percentile for each census division, although both distances contain the same number of buildings. This reflects the skewness of these distributions toward higher EUIs.

Figure 4. *Box Plot Showing Median (Horizontal Line Within Box), 25 and 75% Range Limits (Outer Ends of Box), and 10 and 90% Range Limits (Ends of Stems) for CBECS Office Buildings (Buildings<=1,000,000 sq ft, n=1358)*



The EUI of an individual office building can be compared to the distributions in Figure 4 to identify where it stands relative to other office buildings within its census division. The 110 kWh/sqft building in the South Carolina data set has an EUI more than double that of 90% of all CBECS office buildings in any census division. The highest EUI in the Montana data set is 45 kWh/sf, which is 20% higher than the approximately 38 kWh/sqft, 90% range limit in its corresponding census division 8.

It is important to note that these distributions, though limited to electric use only, include buildings which use all types of heating fuels (electricity included). While this may account for some of the wide variances in the distributions, sizeable EUI variances were also found when electrically-heated and non-electrically-heated buildings were examined separately. This could be largely related to the fact that many office buildings have sizeable internal loads such that heating energy needs are minimal.

Statistics for the South Carolina and Montana data sets are presented alongside their respective census division statistics in Table 2. For census division 5, which contains South Carolina, census division and state average EUIs are near equal and not statistically different. Both the census division and state samples had buildings with excessive EUIs. Medians do not agree as well, suggesting there could be larger differences. For census division 8, which contains Montana, census division and state average EUIs are far apart and are statistically different. There is a very large difference in medians as well. Census division 8 had some excessive EUIs

Table 2. *Comparison Between Census Division Statistics from CBECS and Those from Measured Data on Buildings Within States*

	Census Division 5	South Carolina	Census Division 8	Montana
No. of buildings	234	31	83	27
Median	16.5	13.1	14.9	7.7
Average	20.8	18.4	20.7	10.1

(above 100 kWh/sqft) while the Montana data set did not. Note also, however, that there is a dramatic difference in medians. While only two cases, these results suggest that census division statistics may not always be representative of what can be expected at more local levels.

Modeling

Electricity use as a function of building floor area is show in Figures 5 and 6 for census divisions 1 and 5. Data in census division 1 tend to follow a pattern of increasing electricity use with increasing floor area suggesting a linear relationship. Plots for three other census divisions showed similar patterns. Five census divisions exhibited patterns as shown for census division 5. This trend shows that the variability of electricity use increases with increasing floor area and does not necessarily suggest a linear relationship between electric use and floor area.

Because linear models were to be assumed for the analysis, logarithmic relations between these two variables were examined for linearity. These relations are shown in Figures 7 and 8 for the same two census divisions. A strong linear relationship between electricity use and floor area is now evident. Also, the variances are approximately equally distributed as desired for statistical analysis. Previous work has also found non-linear relationships between electric energy use and building characteristics (Kelso et al. 1995, Burns 1990). The more uniform distribution for census division 5 was typical for most census divisions. The strong correlations between electricity use and floor area provided coefficients of determination (R^2) of between 0.74 and 0.88. For

Figure 5. *Electric Use as a Function of Floor Area for Census Division 1*

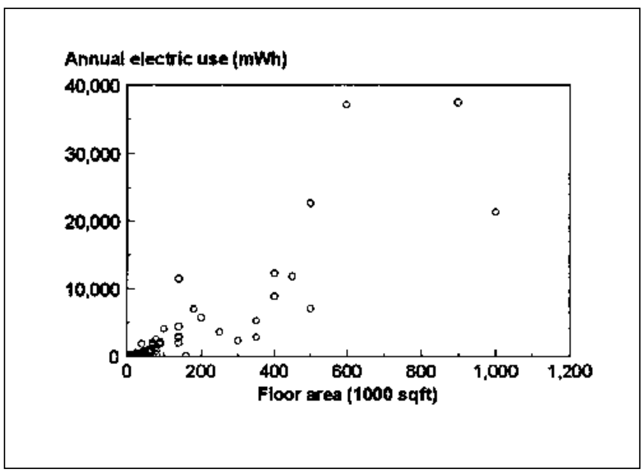


Figure 6. *Electric Use as a Function of Floor Area for Census Division 5*

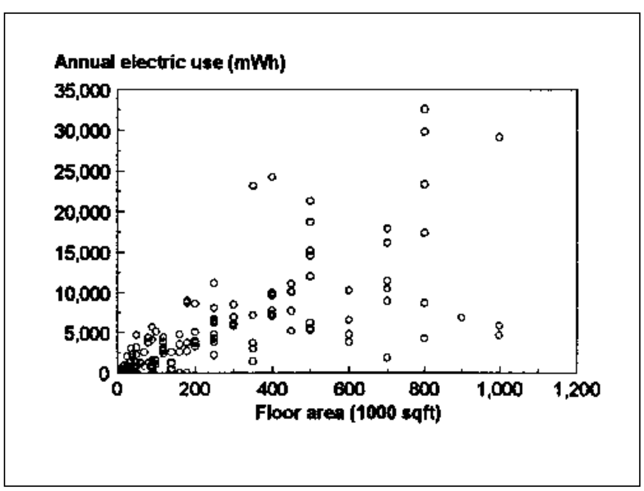


Figure 7. *Electric Use as a Function of Floor Area for Census Division 1 (Logarithmic Scales)*

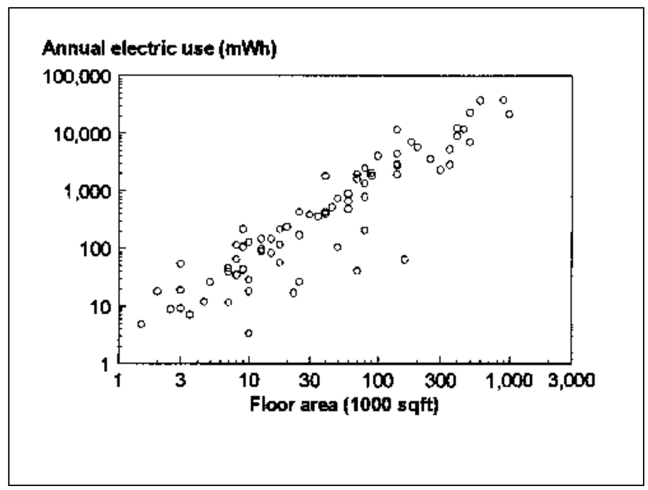
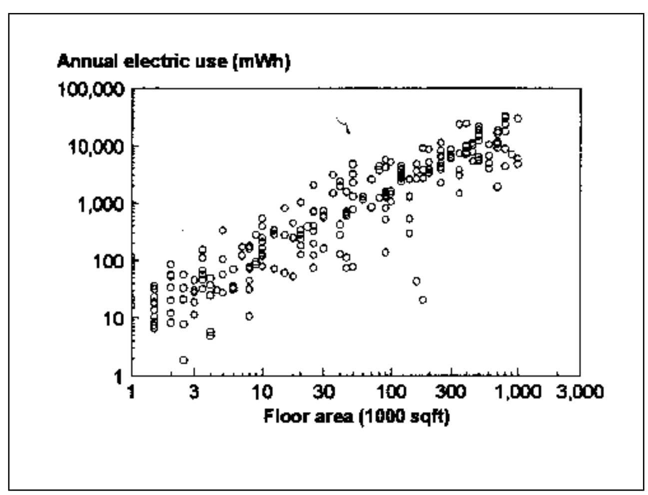


Figure 8. *Electric Use as a Function of Floor Area for Census Division 5 (Logarithmic Scales)*



census division 5, R^2 equaled 0.82, indicating that most of the variation in electricity use in Figure 8 is explained by variations in floor area.

Electricity consumption was normalized by floor area in the regression models due to its strong dependence on area. In addition, the number of workers was also normalized by floor area. A strong correlation between these two variables was also found.

Seventy-five CBECS variables were selected to be examined as determinants of electric energy use intensity in office buildings. These variables were selected based on two criteria. First, they were thought to be some of the more influential relative to electricity use, and secondly, they were reported for most buildings. Stepwise regression was used to model electric energy use per square foot as a function of the CBECS variables. The first analysis step indicated that the 33 variables in Table 3 are significant to electric energy use intensity.

Variables that were the least significant and least common to the nine census divisions were removed from the analysis in an iterative process. This produced six variables which were found to be the most common and strongest indicators of building electric use intensity in the nine census divisions. The two dominant variables (most important) correspond to the logarithm of the number of workers per square foot (log of NWKERSF) and the category describing the number of personal computers in the building (PCTRMC). These are followed by the number of operating hours (WKHRS) and whether the building is owner-occupied (OCCTYP1). The remaining variables of less importance were the presence of an economizer (ECN) and a chiller (CHILLR). Standard linear regression performed on the final six variables was used to determine model coefficients for each census division. Models based on this small number of the strongest variables are much more simple and are good approximations of the estimates that an expanded model based on all significant variables would produce.

The log transformation of the variable NWKERSF was the strongest determinant of electric energy use intensity in four census divisions. The personal computers category variable, PCTRMC, dominated in three census divisions. Owner-occupancy and operating hours dominated in one census division each. The resulting predictive model for electric energy use intensity in commercial buildings is:

$$\log(\text{kwhsf}) = a + b*\log(\text{NWKERSF}) + c*\text{PCTRMC}$$

$$+ d*\text{OCCTYP1} + e*\text{WKHRS} + f*\text{ECN} + g*\text{CHILLR}$$

where ECN and CHILLR have values of 1 if they are present for the building and 0 otherwise. OCCTYP1 is 1 if owner-occupied and 0 otherwise. The number of workers per square foot, the category describing the number of personal computers, and the operating hours vary widely across buildings. Although there are six variables in the general model for all census divisions, individual census division models are comprised of three or less variables each. Per this analysis, these simple models explain almost all of the variation in electric EUIs that can be explained by the CBECS variables analyzed. Coefficients for the predictive models are given in Table 4 for each census division. When applied to the general model, simple census division-specific models will result that can be used to predict office building electric energy use intensity.

The improvements achieved by using estimates from the census division models as benchmarks in contrast to using simple census division averages as benchmarks was investigated. Differences between individual building EUIs and census division averages were compared to differences between individual building EUIs and model results. Results for census divisions 1 and 5 are shown in Figures 9 and 10. Notice in both census divisions that using model results dramatically reduced the negative errors or differences exceeding −11 kWh/sf. Between these two census divisions, 89 buildings had negative errors exceeding −11 kWh/sf when averages were used in contrast to only 25 when using model results (see ranges <= −21 and −20 to −11 in the figures). This indicates that the variables in the census division models do an excellent job of representing the factors that produce high electric energy use intensities in buildings. This is important because it is the higher EUI buildings that are most responsible for the unreliability of average EUIs. Similar results occur in other census divisions.

Of the 234 buildings in census division 5, 114 or 49% exceed errors between −10 and 9 kWh/sqft. These are large errors considering the average EUI for this census division is 20.8 kWh/sqft. When model results are used, only 61 or 26% exceed these errors. This indicates that the census division 5 model almost halves the number of buildings that would otherwise have these larger errors.

CONCLUSIONS

Statistical distributions of office building EUIs developed from CBECS data can be used for comparing the performance of an individual building to others within its respective census division. Median EUIs are more reliable comparators when it is desired to compare the energy use of a sample of local buildings to CBECS census division statistics. Averages can be strongly influenced by a small number of buildings with excessive individual EUIs. This occurs in the CBECS database and will occur in local sampling of office buildings. Based on the limited comparisons here,

Table 3. CBECS Variables Analyzed for Electric Energy Use Impacts

Variable	Description	Variable	Description
CLIMATE	climate zone	CHWT	district chiller water used
YRCON	year constructed	CHWTP	percent cooled by CHWT
HEATP	percent heated	CHILLR	central chillers used
COOLP	percent cooled	PKGCL	package cooling used
WKHRS	weekly hours open	PKGCP	percent PKGCL
NWKER	number of workers	ELHT1	electricity—main heating
BLDSHP	buildings shape	ELHT2	electricity—secondary heating
GLSSPC	glass percent	STCOOL	district steam cooling
NGSUPL	natural gas supplied	LTNHRP	percent lit during off-hours
FKSUPL	fuel oil supplied	FLUORP	percent lit by fluorescent
PCTRMC	number of PCs category	VAV	variable air volume system
OCCTYP1	occupant status	ECN	economizer cycle
HCHRS	extra hours heated/cooled	RIN	roof or ceiling insulation
HDD65	heating degree days	WIN	exterior wall insulation
CDD65	cooling degree days	RDHTNF	reduction in heat off-hours
FURNAC	furnaces heating air used	EMCS	energy management control system
FURNP	percent heated by furnace		

census division average and median EUIs do not appear to be reliable indicators for more localized EUIs.

A variety of indices calculated from CBECS survey data suggest that there are unusual characteristics for many office buildings in the survey. Some of these include buildings with excessively high and low EUIs, excessive or minimal square footage per worker, and buildings where reported floor areas far exceed calculated floor area maximums. Accordingly, CBECS users should be aware of these issues and be careful in the use of some data.

CBECS building characteristics can be used to develop models that can provide much more reliable benchmarks than simple census division statistics. While many CBECS variables are statistically significant as predictors of building EUIs, when analyzed by census division, two or three will provide most of the predictive capabilities of an expanded model. The models developed here are particularly effective as benchmarks for buildings with characteristics that typically produce high EUIs.

There may be opportunity to improve EUI models beyond that achieved using CBECS data. One possibility would be to have additional building characteristics that are known to be major determinants of energy use such as installed lighting wattage or the overall building shell heat transfer coefficient, both of which are unavailable through CBECS data. A second might be to apply numerous screening criteria to the CBECS office building sample in an effort to produce a refined sample for analysis. Ideas might be to exclude buildings with extremely high or low EUIs, to analyze build-

Table 4. ***Values for Regression Model Coefficients***

Census division	Regression Model Coefficient						
	a	b	c	d	e	f	g
1	1.04	.376	.231	0	0	0	0
2	1.62	.609	0	.222	0	.524	0
3	1.41	.499	0	0	.00722	.384	0
4	1.58	.422	.108	0	0	0	.685
5	1.62	.563	0	0	.00802	.350	0
6	1.28	0	.128	.844	.00793	0	0
7	1.86	.630	0	0	.00448	0	.327
8	1.58	0	.170	.624	0	0	0
9	1.27	.406	0	0	.0120	.366	0

Figure 9. *Chart Showing Differences Between Reported and Average EUIs Compared to Differences Between Reported and Model-Predicted EUIs for Census Division 5*

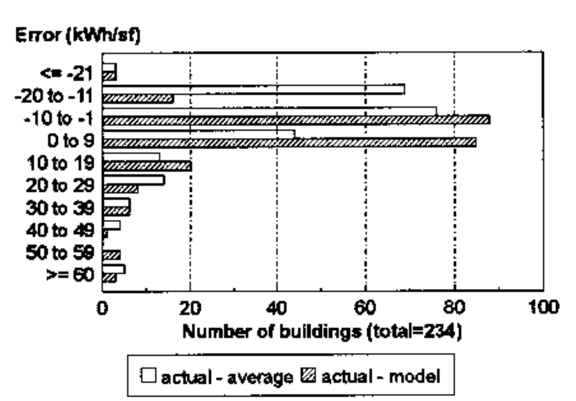
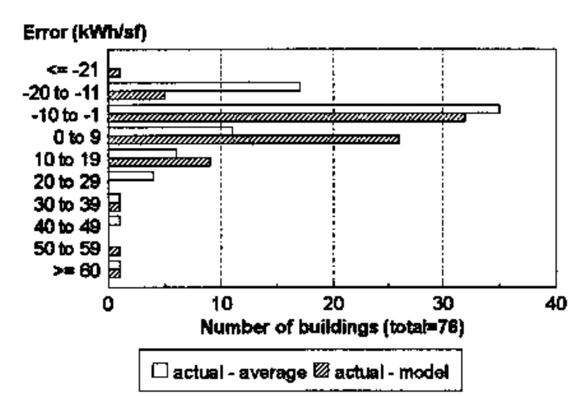


Figure 10. *Chart Showing Differences Between Reported and Average EUIs Compared to Differences Between Reported and Model-Predicted EUIs for Census Division 1*



ings in differing size categories separately, or to exclude buildings with large floor area to worker ratios. Careful application of screening criteria could still yield a subset that would be representative of a large number of U.S. office buildings.

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